Film Material-Scanner Interaction

Flückiger, Barbara ; Pfluger, David ; Trumpy, Giorgio ; Aydin, Tunç ; Smolic, Aljoscha

Abstract: DIASTOR (2013–2015) was an applied interdisciplinary project developed and managed by Barbara Flueckiger. It was one of DIASTOR's main objectives to develop non-destructive, scalable solutions for a variety of film materials in different conditions and for diverse color processes, including a special focus on improving the scanning and rendition of film colors such as early applied colors, Technicolor, Dufaycolor, Agfacolor and additional chromogenic processes. This research is now taken up and extended in the current research project FilmColors, funded by an Advanced Grant from the European Council. Based on insights gathered in the previous projects AFRESA and Film History Remastered, scanning was considered crucial for digitization workflows. Most scanners available are not designed for capturing historical materials but for more recent chromogenic negatives. Therefore, the present scanner study was designed to deliver insights into the material–scanner interaction for a variety of color film stocks, from early tinted film to more recent chromogenic stocks including reversal film. We decided to collect a selection of reference materials, to investigate the technical details of scanners currently on the market and then to test a selection of the most widespread scanners in the high-end domain, currently in operation at archives and service providers for the digitization and restoration of archival films. Our goal was to provide a well-grounded framework for archives and film labs to select scanners according to their needs with a special focus on capturing certain film stocks.

Investigation of Film Material–Scanner Interaction

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[1] University of Zurich, Department of Film Studies: Project manager and principal investigator of DIASTOR (2013–2015) and ERC Advanced Grant *FilmColors* (2015–2020), conducted the Kinetta (by Kinetta), ARRISCAN (by ARRI), Scanity (by DFT) and Golden Eye (by Digital Vision) tests in collaboration with the corresponding facilities, set up the general objective and procedure in collaboration with her team, contributed general information and evaluation to the report, wrote major parts of the report.

[2] University of Zurich, Department of Film Studies: Senior researcher, conducted The Director (by Lasergraphics), D-Archiver Cine10-A (by RTI); Northlight 1 (by Filmlight) and Altra mk3 (by Sondor) tests, elaborated a table with an overview of all the available scanners, set up the general objective and standardization in collaboration with the team, contributed general information and evaluation to the report.

[3] University of Basel, Digital Humanities Lab, under the supervision of Rudolf Gschwind and Peter Fornaro, (until 06.2014). University of Zurich, Research Scientist at ERC Advanced Grant *FilmColors*. Provided major parts of the section *Principles of Material–Scanner Interaction*, *Resolving power and sharpness*, and carried out the spectroscopic analysis of film stocks.

[4] Swiss Federal Institute of Technology, Computer Graphics Lab, conducted evaluation of results.

[5] Disney Research Zurich (DRZ), supervised the evaluation of the results.

[6] Disney Research Zurich: Co-project manager of DIASTOR, group leader at DRZ and supervisor of evaluation of results

Summary

DIASTOR (2013–2015) was an applied interdisciplinary project developed and managed by Barbara Flueckiger.[7] It was one of DIASTOR's main objectives to develop non-destructive, scalable solutions for a variety of film materials in different conditions and for diverse color processes, including a special focus on improving the scanning and rendition of film colors such as early applied colors, Technicolor, Dufaycolor, Agfacolor and additional chromogenic processes. This research is now taken up and extended in the current research project *FilmColors*,[8] funded by an Advanced Grant from the European Council.

Based on insights gathered in the previous projects AFRESA[9] and *Film History Remastered*,[10] scanning was considered crucial for digitization workflows. Most scanners available are not designed for capturing historical materials but for more recent chromogenic negatives.

Therefore, the present scanner study was designed to deliver insights into the material–scanner interaction for a variety of color film stocks, from early tinted film to more recent chromogenic stocks including reversal film. We decided to collect a selection of reference materials, to investigate the technical details of scanners currently on the market and then to test a selection of the most widespread scanners in the high-end domain, currently in operation at archives and service providers for the digitization and restoration of archival films. Our goal was to provide a well-grounded framework for archives and film labs to select scanners according to their needs with a special focus on capturing certain film stocks.

[7] See DIASTOR research project: http://www.diastor.ch. Based at the University of Zurich, the project brought film-historical knowledge and restoration ethics together with advanced research in IT and the technological expertise of Swiss service providers and engineering companies. The goal was to offer custom-tailored solutions that bridge the gap between analog film history and digital technology.

[8] See entry in the research database of the University of Zurich: http://www.research-projects.uzh.ch/p21207.htm [last accessed January 4, 2018]

[9] See entry in the research database of the University of Zurich: http://www.research-projects.uzh.ch/p10747.htm [last accessed January 4, 2018]

[10] See entry in the research database of the University of Zurich: http://www.research-projects.uzh.ch/p15584.htm [last accessed January 4, 2018]

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1 Introduction

The DIASTOR scanner study was established in distinct steps, with several research questions and goals, each of which are interconnected to the others. Samples were scanned on a selection of available scanners. Scanning was executed between 2013 and 2016; the results were evaluated in 2016 and 2017.

In order to receive a rich set of results, the study did not focus on technical data. Such scanner testing has been done before, for instance by the FIAF technical committee.[11] Instead, our investigations targeted the specific needs of scanning historical color film materials that often do not fit the specifications of more recent chromogenic negative stock.

While the DI process has been the standard field of scanning for many years, with a highly grossing commercial potential, current requirements for the digitization and restoration of archival films may deviate considerably with regard to physical and mechanical aspects and image processing.

To meet our goals, we devised several steps and areas of investigation with a variety of methods, from the historical and physical analysis of film stocks, to the technical data of the scanners, measurements and evaluation of results as well as exploration of real-life applications including the scanner operators' background and the institutional framework of the scanners in operation.

- **Collecting information on scanners:**
  We were aiming at investigating the following information to the extent possible and if available. In part they were provided by scanner manufacturers, in part they had to be determined from the scanner tests:
    - Illumination: intensity, spectral power distribution
    - Sensor: resolution, sensor technology, spectral sensitivity
    - Processing, software, controls
    - Focus and depth-of-field
    - Handling
    - Mechanics
    - Questionnaire

- **Influence of operators:**
  One of our most important hypotheses was that the professional background and institutional framework of the scanner operator is crucial for providing satisfactory results. This *human factor* consists of the following parameters:
    - Knowledge of machine and material
    - Experience in processing material with a wide variety of characteristics
    - Personal preferences and attitudes

[11] See http://www.fiafnet.org/images/tinyUpload/E-Resources/Commission-And-PIP-Resources/TC_resources/Digital%20Complications%20v1.1.pdf [last accessed January 30, 2016]

  - Institutional framework, i.e. the archive's or service provider's policies, infrastructures, goals and needs.

- **Different color processes:**
  We have assembled a selection of typical historical film stocks with different material requirements, spectral characteristics and aesthetic appearances. The spectral absorbance of certain sample materials was measured (for details see section *Principles of Material–Scanner Interaction*):
  - Tinting/toning
  - Technicolor No. IV dye-transfer print
  - Kodachrome
  - Dufaycolor
  - Ektachrome
  - Black and white reversal
  - Faded Eastmancolor positive
  - Faded color reversal intermediate

- **Questionnaire and observation**:
  During the scanner study we recorded our observations and took photos to document the different handling steps, settings and decisions executed by the scanner operator. The questionnaire aimed at gathering additional information about options provided by the scanner, mechanical layout of the scanner in processing historical film stocks with shrinkage, damaged perforation, non-standard geometry etc.

- **Selection of scanners:**
  The following scanners were used at the following facilities:
  - DFT's Scanity:
    - Digimage in Paris, operated by Saïd Chaouni, 4K option, 35mm gate only
    - EYE Filmmuseum in Amsterdam (preliminary trials), operated by Annike Kross, 2K option
    - Sound and Vision Hilversum, operated by Paulo Veiga da Fonseca, 2K option
  - Filmlight's Northlight 1:
    - Cinegrell Postproduction in Zurich, operated by David Pfluger
  - ARRI's ARRISCAN:
    - ARRI Munich, operated by Sibylle Maier
    - Cinegrell Postproduction Zurich, operated by Markus Mastaller from ARRI Munich and Nicole Allemann, Cinegrell Postproduction Zurich
  - Lasergraphics' The Director:
    - Institut National de l'Audiovisuel INA, Paris, operated by Jean-Yves Baudon of the Cadre Technique of INA
  - RTI's D-Archiver Cine10-A:

        - AV Preservation by Reto.ch Ecublens, operated by Reto Kromer
    - Sondor's ALTRA mk3:
        - Sondor Willy Hungerbühler, operated by Andrea Braun
    - Kinetta's Kinetta:
        - AV Preservation by Reto.ch Ecublens, operated by Jeff Kreines and at Film-maker’s Cooperative in NYC, also operated by Jeff Kreines
    - Digital Vision's Golden Eye 4[12]

1.1 General Objective

Before scanning the film samples, we executed preliminary trials to devise a standard procedure and identify possible problems. One of the most important obstacles to receive standardized results was the high degree of variance in the layout of the scanners and the very different workflows applied (Figure 1).

Figure 1 Results of preliminary scans: ARRISCAN (top left), D-Archiver (top right), The Director (bottom left), and Northlight (bottom right)

Some of them allowed 4K **resolution**, some only 2K. Each scanner had its own image geometry; each resolution was therefore targeted at differing dimensions of the frame. For instance, only a minority of scanners is capable of capturing the whole film width. On the one hand it would be a requirement for the digitization of archival film to document the non-frame portions of the film, such as perforations, edge codes, information about the dyes applied etc., increasingly a standard practice; on the other hand, capturing the whole film width results in a

[12] The scans on the Golden Eye scanner at Studio Hamburg encountered software problems. The new version of a major update had just been installed and proved not to be working properly. Very few usable results could be acquired. Therefore, the results of the Golden Eye were generally omitted.

lower resolution across the frame. Some facilities and some scanners operate at different **bit depths** and with different **gradations** such as 10 bit log files or 16 bit linear. The bit depth per color channel defined by the sensor when recording the images does not necessarily correspond to the bit depth of the delivered files. Often conversions are performed as part of the machine's workflow without any possibility of influence by the user. The options to **control** parameters during the scanning process as well as the structure of the graphic user interface varied greatly across different scanners. It was not possible to obtain a standardized tone range or histogram.

1.2 Measures Taken to Counteract the Problems

For the evaluations, all the images were normalized by the IT researchers at ETHZ and DRZ. In addition, we attached a standardized leader to each material, one for 35mm films and one for 16mm films.

Test Leader 35mm Film

The leader used for all 35mm materials was a 4K film-out of the ARRI AQUA test leader (Figure 2) made using an ARRILASER on KODAK Color Asset Protection Film 2332. The leaders served as a point of reference constant over all 35mm samples, but were not used to adjust the scanner's settings regarding density and color for the film samples, as the non-standard film materials often required significantly different adjustments on different scanners.

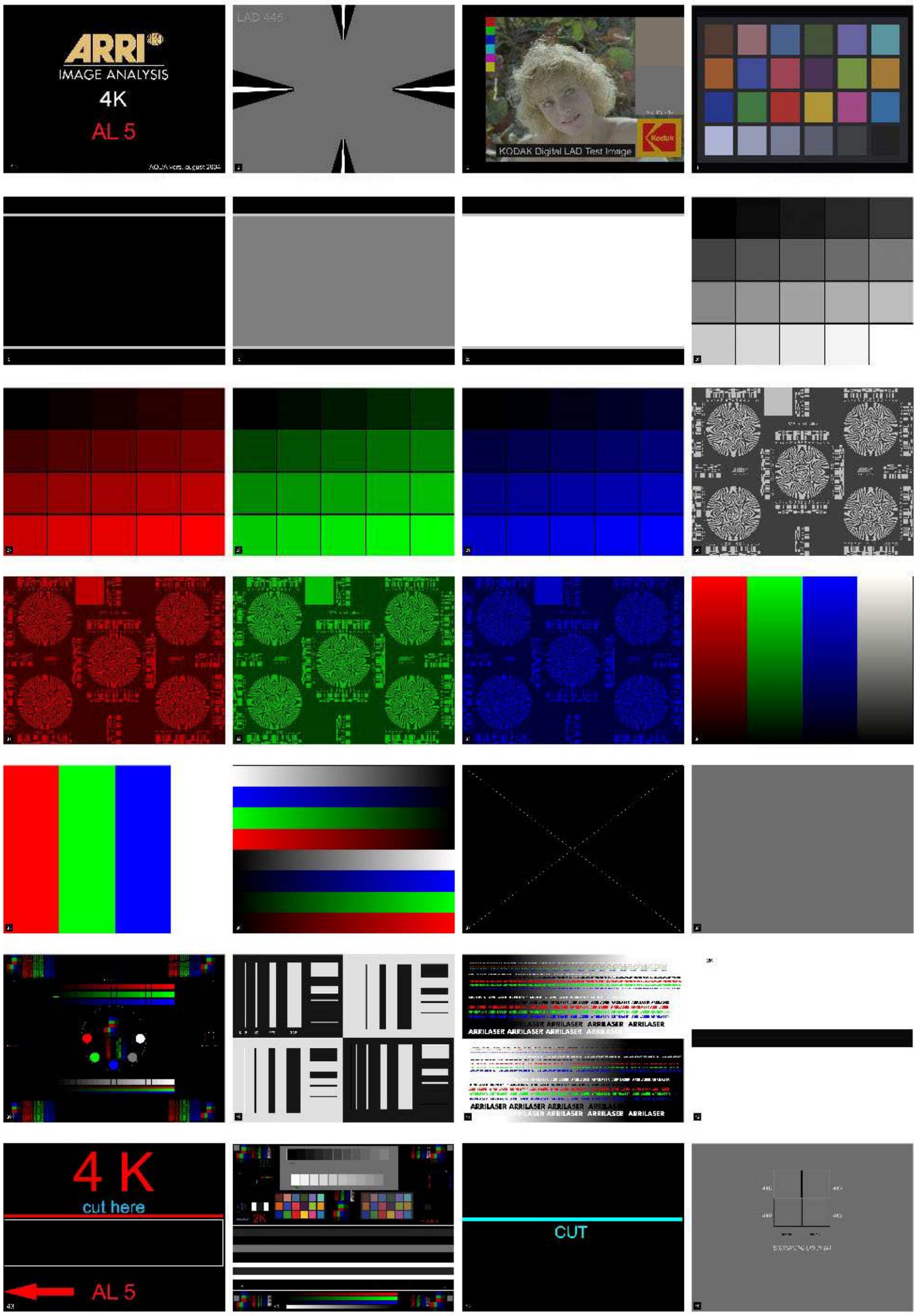

Figure 2 Contact sheet of the ARRI AQUA leader for film-out with a resolution of 4096 x 3112 pixel and a bit depth of 16 bit linear per color channel

2 Principles of Material–Scanner Interaction

Scanners are defined in part by their physical and mechanical operating systems, in part by inherent image processing protocols, controlled through some user interface on a monitor or by hardware controls on the scanners. Therefore, within limitations defined by hardware and software, scanners can be adjusted to various needs and goals. However, understanding the underlying principles of the scanners in operation and analyzing the material properties of several different film stocks was among the most important parts of the present scanner study.

Color films based on subtractive 3-color processes represent the dominant technology since the mid-1950s, and constitute the largest part of film heritage to be digitized. For this reason, many scanner manufacturers used to design their products to excel in the scanning of subtractive 3-color processes, often compromising the performances of the scanner for other kinds of film colors. Thus, to understand the technical characteristics of the scanners on the market, it is helpful to describe the optical properties of subtractive 3-color film, and the principles of its interaction with the scanners' components during image acquisition.

2.1 Optical Characteristics of Subtractive Color film

Broadly speaking, after exposure and processing, the emulsion of a modern color film consists of three adjoining layers, each containing a single light absorbing substance (a dye). Each dye has a different spectral absorption, and its concentration varies across the frame to form the image. One dye absorbs light with the longer wavelengths of the visible spectrum (roughly from 600 to 700 nm) and transmits the remainder, producing a cyan color; another dye absorbs light with wavelengths in the middle of the visible spectrum (roughly from 500 to 600 nm) and transmits the rest, producing a magenta color; the last dye absorbs the visible light with the shortest wavelengths (roughly from 400 to 500 nm) and transmits light with longer wavelengths, producing a yellow color. The absorptions of the three dyes combine on the basis of their local concentrations to produce a multitude of colors. For a quantitative description of the subtractive process, the '*spectral absorbance*' must be considered.

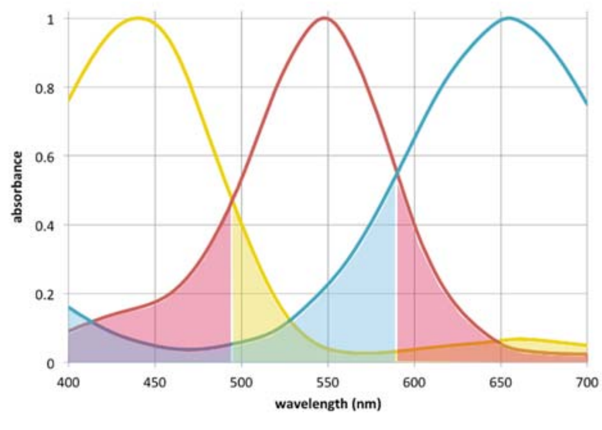

Figure 3 Typical normalized absorption spectra (analytical densities) of yellow, magenta and cyan image-forming dyes of modern chromogenic film. The side absorptions of each dye are highlighted with the corresponding colors.

Figure 3 reports for modern chromogenic film a typical set of absorption spectra (normalized to 1) of the image-forming dyes. These are called *analytical densities*. Beside their pertinent spectral absorption region described above (yellow-short; magenta-medium; cyan-long wavelengths), real dyes have smooth transitions and partly absorb in the other regions. These absorptions are called *side absorptions* (Kowaliski 1977).

The above depiction is quite accurate for reversal film. Negative film stocks, on the other hand, are more complicated due to the *masking* technique used to counterbalance the side absorptions, giving the film the typical orange cast that characterized color negatives starting from the 1950s (Hanson 1950). For the sake of simplicity, we will not take the orange mask into account in the following of this section.

If the film does not scatter light, it is possible to assume that at any wavelength the absorbance of each emulsion layer is proportional to the local dye concentration, and the overall absorbance of the film is equal to the sum of the absorbances of the single layers (considering the film base perfectly transparent) (Hunt 2004). The film can be therefore modeled as a linear system, whose absorption spectrum $A_{film}(\lambda)$ in a certain point is expressed by equation (1) in which the three $\bar{A}(\lambda)$ indicate the normalized analytical densities that are weighted by the factors *K* of local dye concentration (subscripts *Y*, *M*, *C* specify the dye). The spatial indices *x* and *y* define the position on the film area. The absorbances $A_{film}^{(x,y)}(\lambda)$ are called *integral densities*.

$$A_{film}^{(x,y)}(\lambda) = K_Y^{(x,y)} \cdot \bar{A}_Y(\lambda) + K_M^{(x,y)} \cdot \bar{A}_M(\lambda) + K_C^{(x,y)} \cdot \bar{A}_C(\lambda) \quad (1)$$

Another way to express the light absorption by a color film (considered non-scattering) is the *transmittance* $T\%(\lambda)$, i.e. the percentage of transmitted light, which is bound to the absorbance $A(\lambda)$ by the following equation:

$$T\%(\lambda) = \frac{I_{out}(\lambda)}{I_{in}(\lambda)} \cdot 100 = 10^{-A(\lambda)} \cdot 100 \quad (2)$$

For $0 > K > 2.5$ with 0.1 intervals, Figure 4 reports the transmittances of the three emulsion layers of a film with the analytical densities of Figure 3.

A spectral image containing all the absorption spectra of a color film was synthetically assembled with the spectra of Figure 3 and a color scene. The hypothetical film sample appears on a white backlight as Figure 5-*a*. Imagining to physically peel apart its emulsion layers, these would appear as in Figure 5-*b*, *c* and *d*.[13]

[13] The images displayed in Figure 5 were calculated from assembled cube i using the CIE F10 standard illuminant and the CIE 2° standard observer.

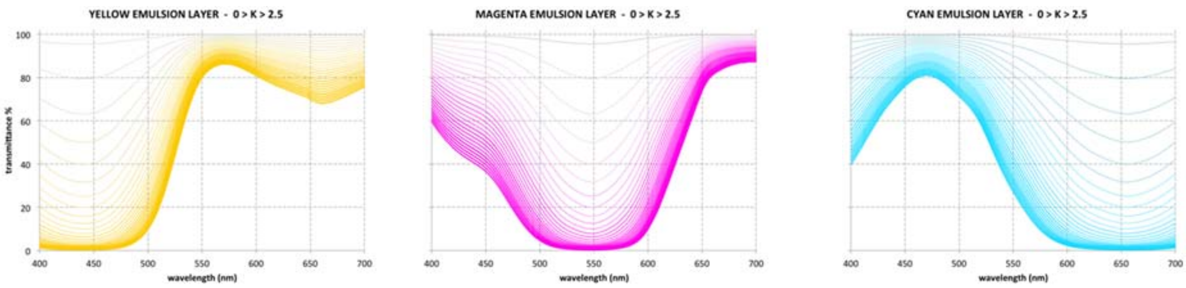

Figure 4 Transmission spectra of the yellow, magenta and cyan image-forming dyes of the film with analytical densities reported in Figure 3. For each dye, the lines correspond to different concentration factors.

Figure 5 Simulated appearances on a backlight for a color film and its single emulsion layers

2.2 Digital Scanning

Scanning a color film is a multi-step process that creates a digital file. Manufacturers of film scanners developed a variety of different solutions to accomplish this process, which nevertheless share some fundamental aspects.

The first step is the emission of light by a source that illuminates the film. Given the spectral power distribution $I_{in}(\lambda)$ of the illumination, the transmitted spectral intensity $I_{out}(\lambda)$ is determined by the overall light absorption in each specific point of the film (see previous section):

$$I_{out}^{(x,y)}(\lambda) = I_{in}(\lambda) \cdot T\%_{film}^{(x,y)}(\lambda) = I_{in}(\lambda) \cdot 10^{-A_{film}^{(x,y)}(\lambda)} \tag{3}$$

The transmitted light is then refracted by an optical system to be focused on a sensor that is composed by a set of independent photosensitive elements, which correspond to the *pixels* of the digital representation. Letting the spatial coordinates x and y assume discrete values with spacing equal to the pixel size projected on the film by the optical system, for each x-y pair the transmitted light $I_{out}^{(x,y)}(\lambda)$ is transduced into one pixel.

The photosensitive element converts the light into electric charges, and then these into voltages. The number of voltage levels that a sensor can output (*Dynamic Range*) is determined by the ratio between the maximum charge that each sensor element can hold (*Full Well Capacity*) and the noise charge generated by the electronics while making a read (*Read Noise*). The dynamic range is often expressed in *dB*, using the following equation:

$$Dynamic\ Range\ (dB) = 20 * log_{10}\left(\frac{Full\ Well\ Capacity}{Read\ Noise}\right) \tag{4}$$

The dynamic range is one of the important characteristics of light sensors. A scanning system with a higher dynamic range allows measuring light more accurately and produces better images.

The A/D converter transforms the voltages into binary numbers. To make the best use of the dynamic range of the sensor, the number of bits (n) used by the A/D converted has to provide at least the number of voltage levels output by the sensor:

$$2^n - 1 \geq \frac{Full\ Well\ Capacity}{Read\ Noise} \tag{5}$$

As any conventional color-imaging device does, film scanners store color information with three values (whatever is the color space eventually chosen, such as RGB, CIE_XYZ, YUV), thus requiring three gray-scale images to be created. For correct color acquisition, the three digital images have to correspond to three specific spectral regions of the visible range, roughly corresponding to the long (R), medium (G) and short (B) wavelengths of the visible range, such for instance the spectral sensitivities reported in Figure 6. The creation of these three images can be done with an actual triple light measurement for each pixel (often advertised by scanner manufacturers as '*true RGB*'), or with a single light measurement for each pixel, reconstructing the other two values by interpolation processes (as carried out by systems with *color filter arrays*).

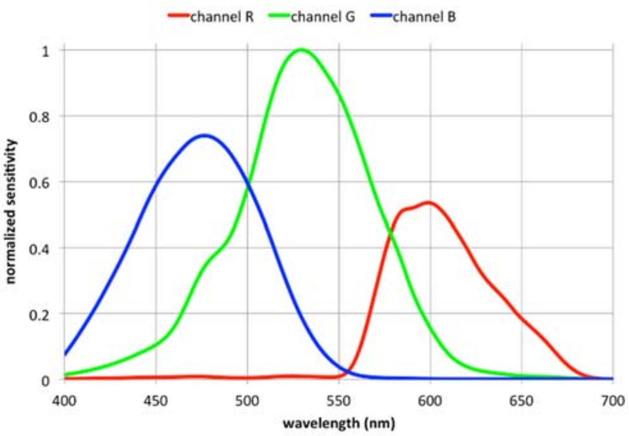

Figure 6 Typical normalized spectral sensitivities of a color imaging device

2.3 Color Separation

The intention of the digitization of a motion picture film is to obtain the most accurate possible reproduction of its colors and to translate with digital technologies the image projected on the screen. In the ideal case of having a pristine projection print that carries the images to be reproduced, the material should be digitized and processed aiming at the maximum color accuracy to the visual appearance on screen.

The acquisition of images with a white broad-band light and an imaging device with a color sensor (e.g. with the spectral sensitivities reported in Figure 6), together with the adoption of accurate procedures of color management, can provide a sufficient color accuracy.

However, in the practice of preservation and digitization of historical film, a multitude of sources can be found (camera negatives, intermediate material of various nature, varieties of projection prints with different appearances), requiring an extensive research on the film's aesthetics to arrive to the proper color balance. Moreover, faded films constitute the majority of color film heritage shot between the early 1940s, when Agfa introduced the first chromogenic negative–positive stock Agfacolor, and the early 1980s, when the fading problem became obvious and manufacturers started producing more stable chromogenic films.

In view of all this, the accurate colorimetric rendition is not necessarily the final goal of the digital migration of a subtractive 3-color film. In case of intermediate material, even more so if the colors are faded, it is opportune to retrieve the largest amount of color information (Trumpy and Flueckiger 2015, Flueckiger et al. 2016). This information is recorded in the single emulsion layers as dye concentrations ($K_Y^{(x,y)}$, $K_M^{(x,y)}$, and $K_C^{(x,y)}$, of equation (1)).

The impossibility to physically separate the emulsion layers forces to seek a method to minimize the effect of the *side absorptions* (Figure 3) and effectively extract the color information. Scanner manufacturers generally refer to this task advertizing the scanner capability to obtain *excellent color separation*. A viable method to obtain good color separation is to narrow the scanner spectral bands, excluding the *transition regions* without a 'dominant' dye absorption.

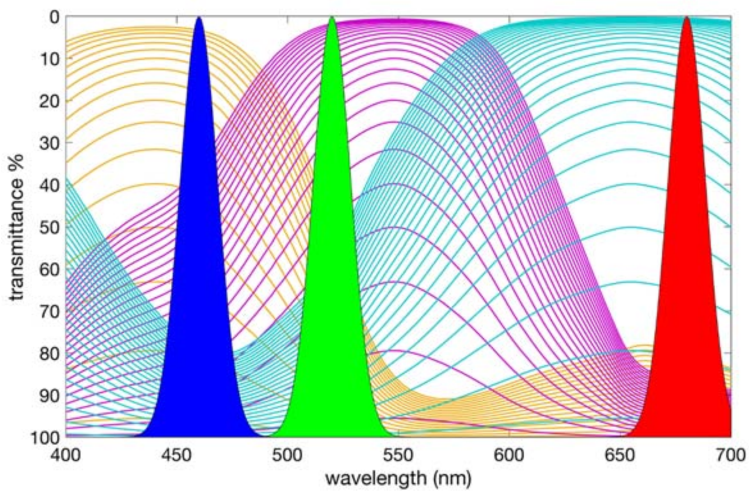

Figure 7 Transmittances of the individual emulsion layers for several dye concentrations. Three narrow spectral bands that maximize color separation are overlaid.

The peak wavelengths of the three narrow bands have to be in spectral positions where the light absorption of one dye is highest, while, at the same time, the light absorption of the other two dyes is lowest. In Figure 7 the recounted analytical densities (Figure 3) are reported as transmittances – therefore with inverted axis – for typical concentration ranges. In the same plot three spectral bands (FWHM = 20 nm) are superimposed, being positioned at around 460, 520 and 680 nm. At these spectral positions the color separation is augmented, and the resulting images are predominantly determined by one specific dye.

The three images have to be combined in a color space. A simple approach is to merge the images in a RGB space, assigning each image to the corresponding channel (image captured with blue light to B-channel, green light to G-channel, and red light to R-channel). Other more complex solutions can be developed for this merging process.

Figure 8 reports the images of a slightly faded frame of chromogenic color film stock from the HEIDI television series (CHE 1978) captured in two modalities. The image on the left was acquired with a broad-band white light and a color sensor. On the other hand, the image on the right was acquired with three narrow-band lights and a monochrome sensor, following the principle of maximum color separation.

The colors of the image captured with narrow-band lights (Figure 8-b) are more vivid: no processing would retrieve those colors from the image captured with white light and color-sensor (Figure 8-a).

Figure 8 Digital reproduction of a frame of HEIDI with different approaches: visual accuracy (left) and color separation (right)

2.4 Analyzed Scanners

For the film scanners analyzed during our study, Table 1 collects the information relative to the method adopted by each of them to produce color images. The subsequent text underlines and explains the different approaches, discussing the features that have an effect on image quality.

Table 1 Light source and image capture sensor properties of the scanners analyzed within this study

Scanner	Light Source			Image Capture Sensor				
	Type	Color components	Directional characteristics	Type	Shape	Chromaticity	Dynamic range	Interpolation Bayer Sensor
1) Sondor Altra mk3	LED	R, G, B	Diffuse	CCD	Area	Color	64 dB (KAI-04050)	Yes
2) CIR D-Archiver Cine10-A	LED	WHITE	Diffuse	CCD	Area	Color	60 dB (KAI-4021)	Yes
3) Kinetta	LED	R, G, B + WHITE	Diffuse	CCD	Area	Color	70 dB (KAI-16070)	Yes
4) Lasergraphics Director	LED	R, G, B	Diffuse	CCD	Area	Monochrome	no data available	No
5) Digital Vision Golden Eye	LED	R, G, B	Diffuse	CCD	Trilinear	Color	dB no data available, ADC 16 bit	No
6) FilmLight Northlight 1	HTI	WHITE (+ MSO Filter)	Diffuse	CCD	Trilinear	Color	no data available	No
7) DFT Scanity	LED	2R, G, B integration sphere + beamsplitter	Diffuse	CCD	3 x TDI linear	Monochrome	dB no data available, ACD 14 bit	No
8) Arri ARRISCAN 4K	LED	R, G, B	Diffuse	CMOS	Area	Monochrome	dB no data available, ADC 14 bit	No

2.5 Single Versus Composite Light

No spectral composition is optimal for all cases. For instance, in the case of negative film with a correction mask, it is preferable to illuminate the film with a bluish light that compensates for the orange of the mask, and not all masks are of the same orange. A scanner with a single-component white light has a fixed spectral composition illuminating the film. When scanning a masked negative with this type of scanner, the proper whitepoint (which becomes the blackpoint after inversion) of the digital image can only be achieved in post-processing, setting the white to the unexposed part of the negative film.

On the other hand, the possibility to independently adjust the constituents of a composite light allows for making the best use of the sensor's dynamic range for all three spectral bands in all situations.

For these reasons, we emphasize the difference between scanners that use a single white light (no. 2, 6 and 7 in Table 1), and scanners that use a lighting system composed of three (no. 1, 4, 5 and 8) or more (no. 3) lights with different spectral emissions.

If the white balance is conducted in the digital domain, only the most exposed channel makes the best use of the sensor's dynamic range, resulting in an image with a reduced wealth of colors. It is therefore preferable to use a scanner with composite light that allows balancing the white in the 'physical' domain.

2.6 Area Versus Line Sensor

Another important distinction is between scanners that use an area sensor (no. 1, 2, 3, 4 and 8), acquiring the images in one shot, and scanners that use a linear sensor, building the images progressively while the film moves in front of the sensor (no. 5 and 7), or while the sensor moves in front of the film (no. 6).

In order to avoid motion blur, the scanners that use area sensors either pulse the light intermittently to limit the exposure time (no. 1, 2 and 3) while the film moves continuously, or alternatively they stop the film at each frame and the light flashes sequentially the three light components for every single frame,[14] acquiring the image of each spectral band with a monochrome sensor. The three monochromatic images are merged to create a *true RGB* color image. All other scanners that use an area sensor (no. 1, 2 and 3) use a Color Filter Array (e.g. Bayer array) and require interpolation to generate the color image. All the tested scanners that use linear sensors, either single trilinear (no. 5 and 6) or three *Time Delay and Integration Sensors* (TDI) (no. 7), do not interpolate and carry out an actual triple light measurement for each pixel.

Considering equal pixel sizes, 'true RGB' is by definition a more accurate color measurement.

2.7 Color Separation

A very important factor to assess the quality of a film scanner is the level of *color separation* of its digital files (see section 2.3).

The analyzed scanners use different methods to exclude the transitional spectral regions and increase the color separation. The prevalent method is to use a composite light with narrow-band constituents (no. 1, 3, 4, 5 and 8). With scanner no. 3 it is even possible to regulate the color separation by adjusting the contributions of the broad-band white LED and the narrow-band LEDs (Red, Green and Blue).

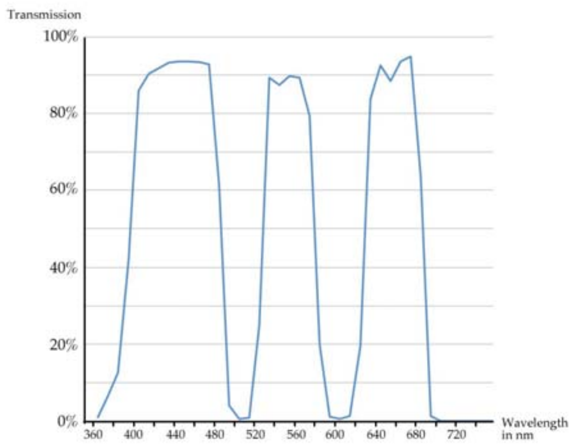

Figure 9 Transmission spectrum of the MSO filter used by Northlight 1

Scanner no. 7 creates three images simultaneously with three monochromatic TDI sensors, on which a beam-splitter assembly distributes spectrally selected images. At the exits of the beam-splitter color filters block out two of the three LED emissions coming from the lamp house. The transmission ranges of the filters are 390-490 nm for the blue, 510-570 nm for the green and 630-770 nm for the red channel. The spectral bands are defined by the LEDs. Their wavelengths are reported in chapter 3.2.

[14] In case HDR or super-resolution is performed, the number of flashes for each frame becomes higher.

Scanner no. 6 excludes the transitional regions where the dye absorption spectra are crossing around 500 and 600 nm with a special filter (MSO filter – spectrum reported in Figure 9).

2.8 Other Historical Color Film Stocks and Further Considerations

In the prior chapter, the interaction between film material and digital scanners applied to the case of subtractive chromogenic 3-color film stock was described. With the color of other historical film materials, other kinds of approaches must be adopted. Tinted and toned films, for instance, contain a wide variety of dyes or pigments, each with its own individual characteristics. As DIASTOR's color analysis for the digital restoration of DAS CABINET DES DR. CALIGARI[16] has shown, it is often very difficult to capture and render the appearance of early applied colors, especially when tinting and toning are combined as in CALIGARI's frame narrative (Flueckiger 2015). The preliminary scanner trials confirmed this problem; some of the scanners were completely unable to capture the blue tinting of the sample provided. They were, as one manufacturer put it, color blind in the spectral range of the dyes in question.

In her master thesis on the restoration of Gasparcolor, Andrea Kraemer (2014) has elaborated on why current digital systems have a smaller gamut than Gasparcolor, which contains dyes in green-blue range currently outside of this coverage.

While it has not always been possible to obtain information about the scanners' spectral sensitivity, we were able to measure the spectral characteristics of the film stocks, as will be elaborated in the corresponding section below.

In summary, our efforts to receive good results scanning historical color film stocks were encumbered by the currently limited modularity of most film scanners. The machines we investigated generally do not allow the required adjustments. Many of the scanner models do not have a modular design which would make the necessary modifications easy to accomplish. With regard to the willingness of manufacturers to answer specific questions and release technical details about their machines, the level of cooperation we received varied broadly.

2.8.1 Tinting

One of the most common early applied colors is tinting.[17] Tinting means the application of dyes by submerging the film positive into a dye bath. This technique requires separating the corresponding fragments to be dyed in batches of different colors. The usually acid aniline dyes form a bond with the gelatin of the emulsion layer. Tinting can be identified by the uniform coloring of the emulsion over the whole film width including the perforation area.

For the scanner study we chose a short fragment of deeply saturated green-blue tinted nitrate film, provided by DIASTOR team member David Pfluger from his own collection.

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[16] Digital restoration supervised by Anke Wilkening, Friedrich Wilhelm Murnau Foundation, Wiesbaden, and executed by L'immagine ritrovata in Bologna.

[17] See detail page "Tinting" on the Timeline of Historical Film Colors http://zauberklang.ch/filmcolors/timeline-entry/1216/

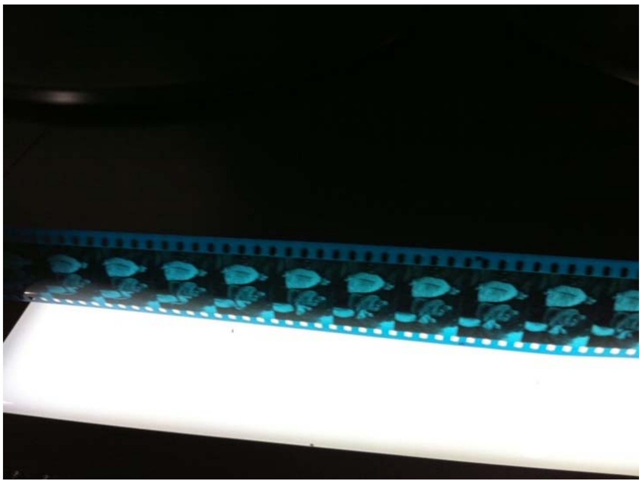


Figure 10 Smart phone photo of the film sample with a blue tint placed on a light board

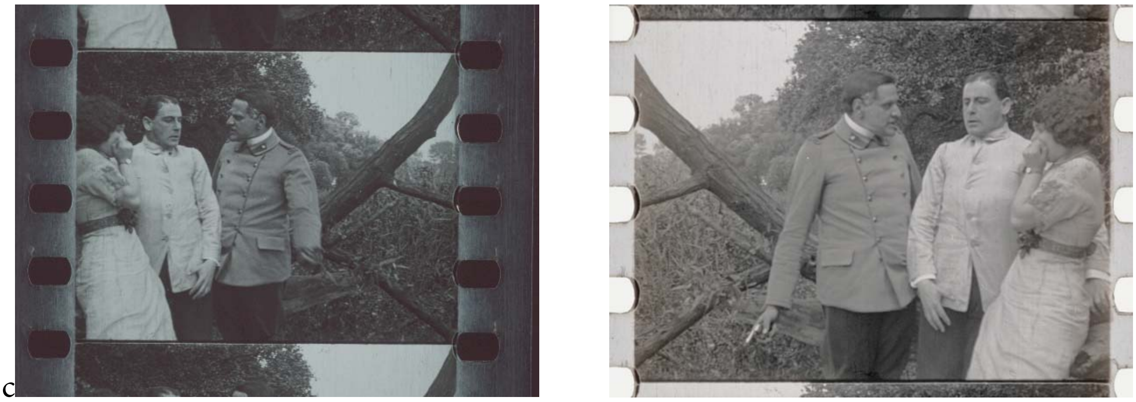


Figure 11 Results from scanning the tinted sample on two different scanner models

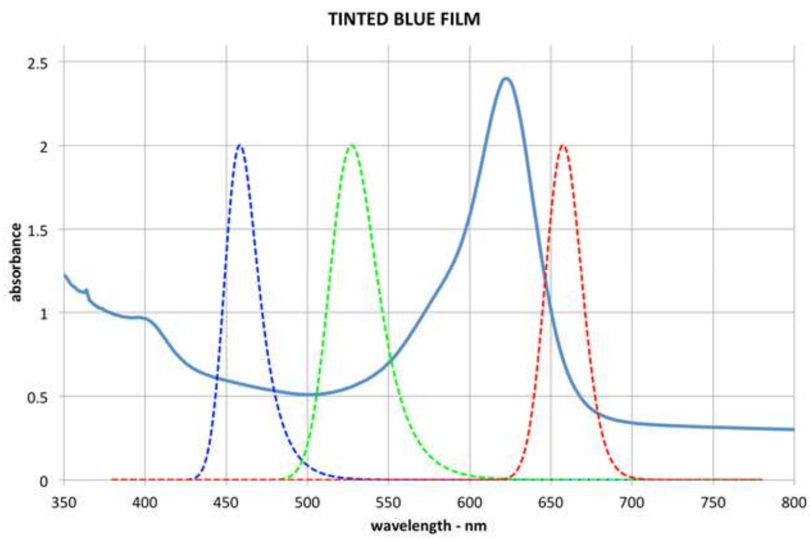
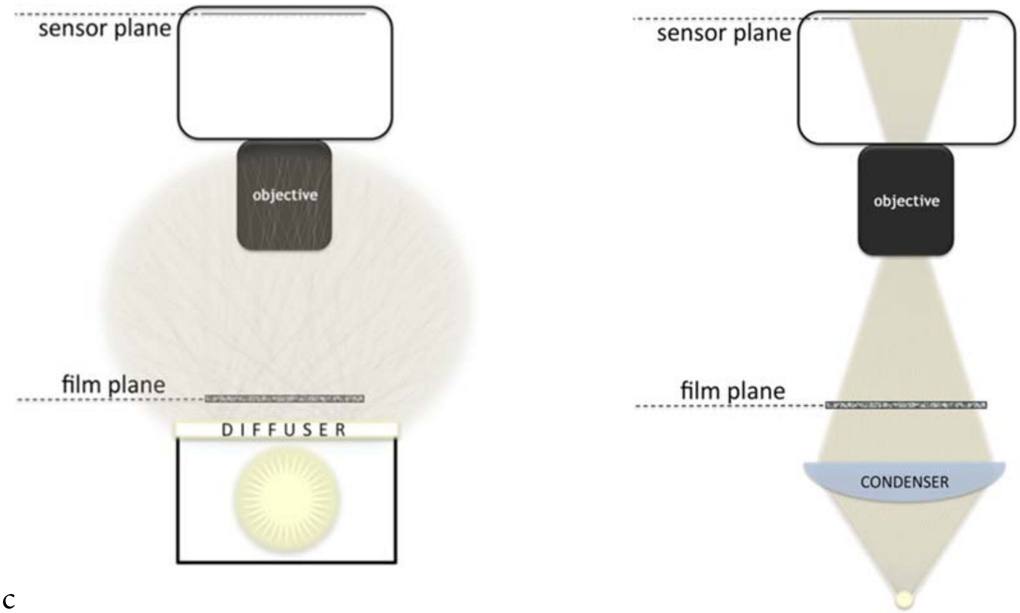


Figure 12 Measurement of the blue tinting dye with the bench spectrophotometer SHIMADZU UV-1800 (solid line). The emissions of the typical lights of a film scanner designed for high color separation are overlaid (dotted lines).

Initially we chose this tinting for the scanner study because of the dark, saturated dye, anticipated as potentially posing a special problem for scanners to be processed because of its density. During the preliminary scanner trials, we noticed that some of the scanners were not able to capture the blue coloring (Figure 11). The spectral analysis executed with the bench spectrophotometer SHIMADZU UV-1800 identified the characteristics shown in Figure 12.

Two RGB reproductions of the blue tinting were created with a **Canon 5D Mark II** digital photo camera as well: the first was created in a diffused bright-field setup (diffuse illumination), the second in a condensed bright-field setup (collimated illumination) as shown in Figure 13.



c

Figure 13 Diffuse (left) versus collimated (right) illumination

The collimation of the illumination plays a fundamental role in the sharpness and contrast of the silver image formed in the emulsion. In fact, in Figure 14 the image on the right is much ‘crisper’ and scratches are emphasized; the image on the left appears ‘softer’ and the details are smoothed. Moreover, the contrast on the right is much stronger than on the left.

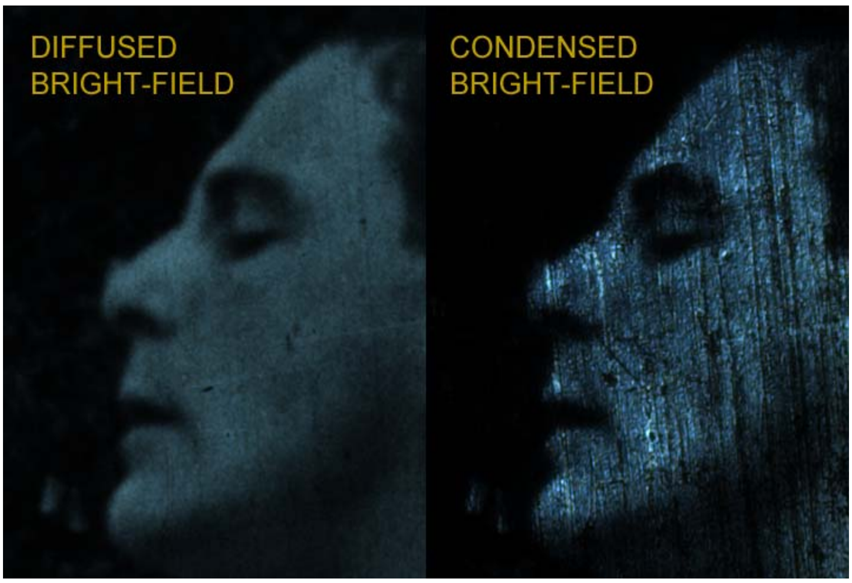


Figure 14 Excerpt of a frame of the tinted sample acquired through illuminating with diffuse (left) versus collimated (right) light source showing the Callier effect and a change in color cast

The phenomenon is known as the *Callier effect*, named after André Callier (1909, see also Mees 1942: 242) who defined the **Q factor**, i.e. the ratio between the attenuation provided by a specific point of a photographic film, measured in directed D_{dir} and diffused D_{dif} bright-fields. The Callier effect is highly important in the context of film scanning, because film projectors use collimated illumination while scanners generally operate with diffuse lights. This can create consistent differences between the digital reproductions of films and their appearance on screen during analog projection, which should actually be the desired visual result for the digital representation (João Oliveira in Busche 2006).

The Callier Q factor is always equal to or greater than one; its trend versus the diffusely measured density D_{dif} is shown in Figure 15 for a typical silver-based film.

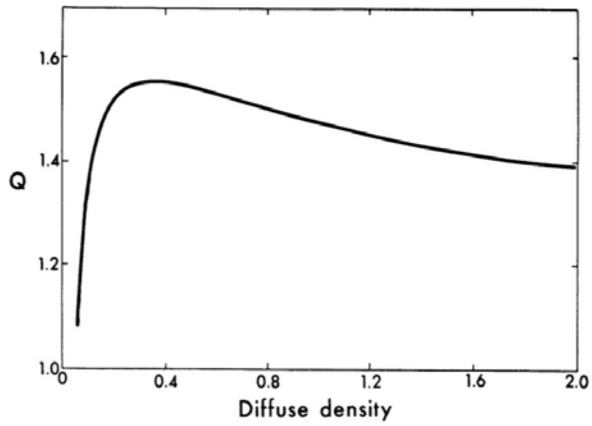


Figure 15 Callier Q factor plotted versus diffuse density

The color balance of the reproductions of the tinted film in diffused and condensed bright-fields have been corrected by setting the white point in an area without film. The main difference between the two images corresponds to the sharpness and contrast; in addition, they have a quite **different color cast**. The image on the left is more greenish, while the image on the right is more bluish.

This difference caused us to speculate that the **Q factor might be wavelength-dependent**. In other words, the plot of the Q factor displayed above might differ for different illuminating wavelengths.

For example, the increment in contrast passing from a diffused to a condensed bright-field might be higher for short wavelengths than for long ones; this would give an explanation to the change in the color cast of the images acquired in diffused and condensed bright-field.

The dependency of the Q factor with the illuminating wavelength might explain the mismatch between the color appearance of a tinted film when it is displayed on a light-box and when it is projected on screen.[18]

An accurate investigation in this direction would be of great interest, in particular for tinted and toned films; in fact, tinted films contain the silver that produces the Callier effect; at the

[18] In the framework of the current research project ERC Advanced Grant *FilmColors*, further tests were executed to investigate the wavelength dependency of the Q factor (Trumpy and Gschwind 2017).

same time, their color hues have a paramount importance for their aesthetics and narrative impact.

2.8.2 Three-strip Technicolor

From the mid-1930s to the early 1950s Technicolor No. IV was the dominant color process in film production, especially in mainstream film. The dye-transfer process required the recording of three black and white negatives in a special camera. From these separations, matrices were produced by tanning that hardened the silver containing parts of the emulsion. The non-hardened parts were subsequently washed off, thereby producing three reliefs that absorbed the three subtractive printing dyes yellow, cyan and magenta. During dye transfer these dyes were applied onto the emulsion of the positive. The positive contained the silver soundtrack and a silver matte for the frame area, sometimes also a weak silver image—called key image—to enhance sharpness. Technicolor films have a unique look defined by high contrast, a rather coarse continuous-tone texture, and highly saturated and dense hues.

During the several decades of Technicolor's color film production, a variety of dyes were applied. The development and application of these dyes has not been documented to date.[19] Therefore, we carried out a procedure to extract the analytical densities of the three dyes from the film stock used for the scanner study. The film positive was a Technicolor trailer of SAMSON AND DELILAH (USA 1949, Cecil B. DeMille), acquired on eBay by Barbara Flueckiger.

The peaks of the eigenspectra are at the following wavelengths:

- Yellow dye $\approx$ 460 nm
- Magenta dye $\approx$ 540 nm (main) and 575 nm (secondary)
- Cyan dye $\approx$ 660 nm (main) and 720 nm (secondary)

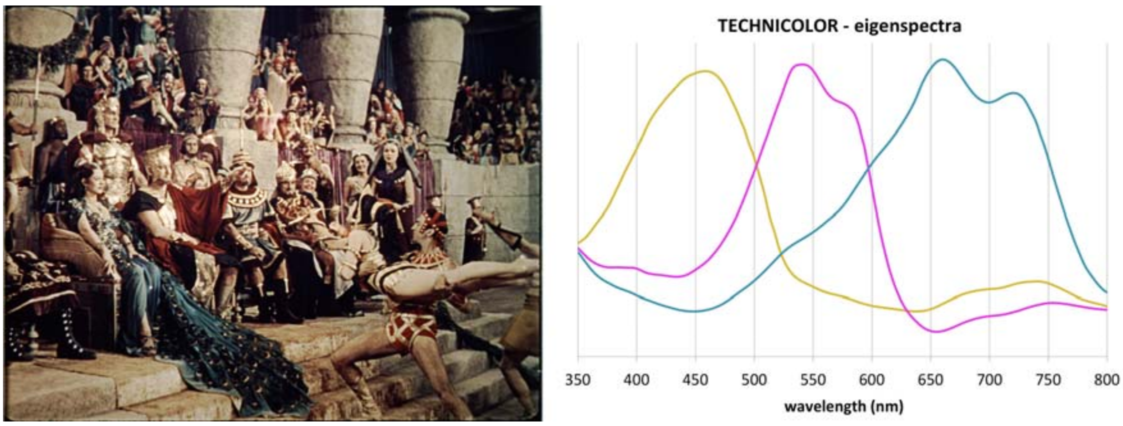


Figure 16 A frame of the analyzed Technicolor SAMSON AND DELILAH and its corresponding absorbance curves resulting from the Principal Component Analysis

A set of points of intense color have been selected from different frames of the film reel, and spectroscopic measurements were carried out with the SHIMADZU UV-1800

[19] A large collection of dyes has been on display at the George Eastman Museum since the Technicolor exhibition in 2015.

spectrophotometer. Twenty-four points were measured; the resulting spectra have been used to apply the *Ohta method*, which is a statistical method that allows estimating the absorbance spectra of the single dyes from their mixtures (Ohta 1973: 553–557). The method consists in applying a *Principal Component Analysis* (PCA) to the measured spectra of a comprehensive set of saturated colors; a prominent difference is generally found between the third and fourth eigenvalue, consistent with the number of independently variable components (i.e. the three dyes). The real absorbance spectra of the constituent dyes can be estimated by finding the proper linear combination of the three e*igenspectra* with the highest eigenvalues; Ohta (1973: 553–557) suggests narrowing the range of possible linear combinations of the eigenspectra by supposing reasonable assumptions (e.g. that spectral absorptions and concentrations of the dyes are always non-negative). We propose achieving an approximation of the spectra of the dyes by performing a minimization with a linear least-squares method to the ideal block dyes (to which every set of dyes refers).

The eigenspectra obtained by applying this method to the Technicolor sample used for the scanner study are reported in Figure 16. The eigenspectra corresponding to the cyan and magenta dyes exhibit double absorption peaks, while the eigenspectrum that corresponds to the yellow dye shows a single absorption peak.

2.8.3 Dufaycolor

Very early in the 20th century ideas emerged to capture colors through colored filters. The Lumière brothers' Autochrome process famously used colored potato starch grains to provide a random screen for the additive rendition of colors in still photography. Similar to Pointillist paintings, these additive patterns of red, blue and green dots or lines create a color impression in the eye of the beholder. In contrast to the random disposition of the Autochrome colored filters, the Dufaycolor is characterized by a regular structure of red, green and blue stripes at a vertical angle of 23°.

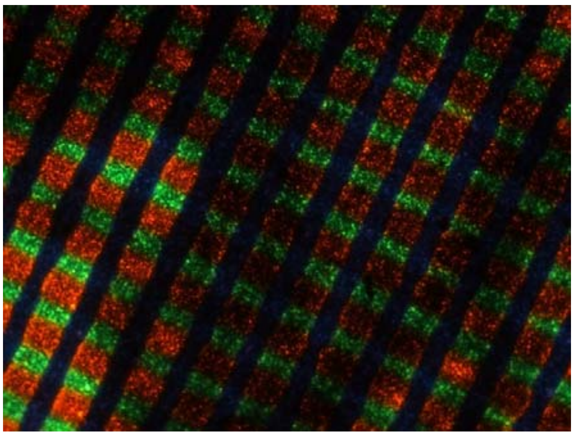


Figure 17 Photomicrograph (twentyfold magnification) of the Spicer-Dufay réseau (Silvana Konermann, MIT)

The Dufaycolor sample used for the scanner study was a short diacetate fragment, provided by the Cinémathèque suisse, depicting a group of pigs.

Like all the line screen and mosaic screen processes, Dufaycolor consists of a black and white emulsion layer combined with the filter layer. Exposure is taken through the filter layer to selectively affect the silver halides. Due to this layered composition Dufaycolor can be scanned either through the base or through the emulsion side. Depending on depth-of-field captured by a scanner, results differ accordingly and require a curatorial decision.

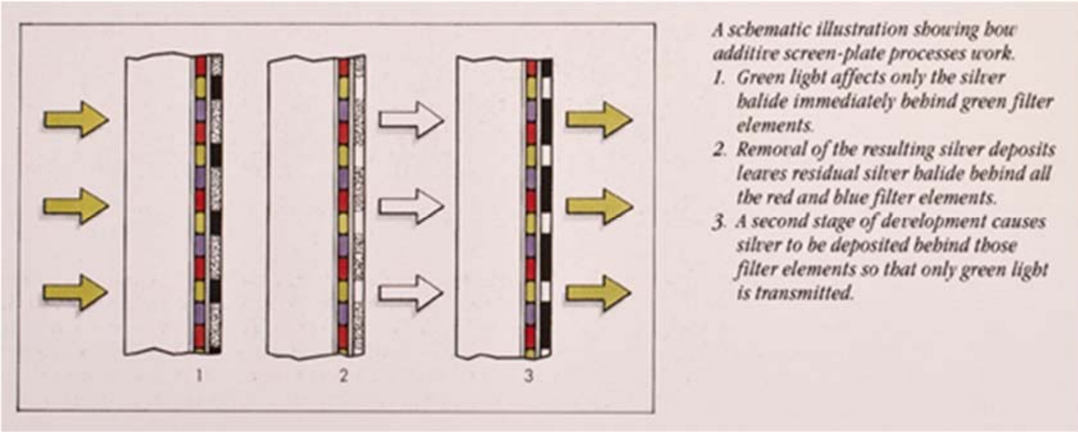


Figure 18 Illustration of the additive screen-plate process (Source: Coote, Jack H. (1993): *The Illustrated History of Colour Photography*. Surbiton, Surrey: Fountain Press)

The Dufaycolor's réseau (Figure 17) consists of alternating green and blue lines interrupted by continuous orthogonal red lines. The whole grid structure is rotated by 23° from the vertical. The line spacing for the three colors is about 500 lines per image in width, being clearly visible in cinema projection, as confirmed in a screening at Lichtspiel / Kinemathek Bern. Only in the last rows of the cinema did the lines fuse into an impression of continuous hues. (The width of the projected image was 4.28 m; the first of six rows of seats was at a distance of 5.30 m from the screen, the last row at 12.30 m; the Kinoton FP38 projector was standing at a distance of 16.30 m from the screen.) A 2K resolution provides a pixel size that is about four times smaller than the line spacing of the Dufaycolor réseau. The réseau appeared blurred in 2K, even when scanned with Scanity's monochrome sensors. DIASTOR partner Reto Kromer suggested that the scanner sensor should be adjusted to the angle of the réseau at 23°, thus eliminating the moiré effect resulting from the diagonal lines interacting with the horizontal and vertical pixel structure of the recording chip. This sensible strategy is prohibited only by the lacking mechanical flexibility of most of the film scanner models.

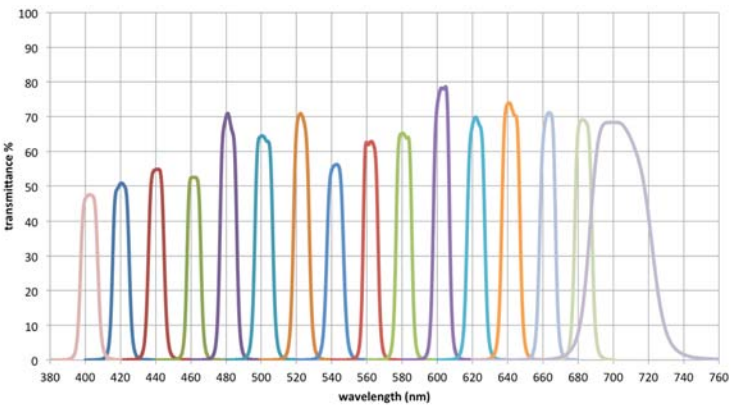


Figure 19 Transmittance of the interference filters used to analyze the Dufaycolor film

For the spectral analysis of the dyes used in the Dufaycolor sample a LEITZ DIALUX 20 microscope with a 40X magnification lens was used. The microscope was equipped with a Carl-Zeiss AxioCam HR 13 Megapixel camera. A set of 16 bandpass interference filters (Andover) with 10 nm bandwidth was used to produce a series of narrow bands at regular steps of 20 nm distance between 400 nm and 700 nm, as shown in Figure 19. To improve the conditions for the measurement of the dye's absorption spectra, a bright area of a film image without significant silver grain density was selected. For each interference filter, an image of the selected area was acquired.

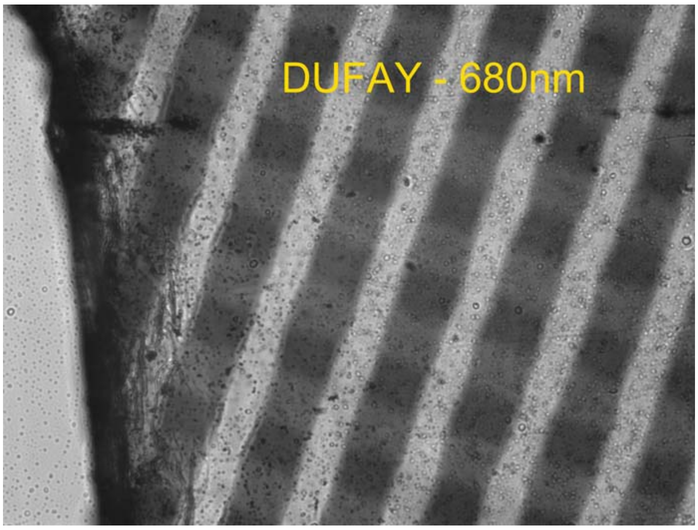


Figure 20 Magnification of the réseau at 680 nm

The images were acquired using 14 bits and then saved in linear mode in TIFF/16 bit grayscale format. Transmittance images were calculated with equation (6) with *white_ref* being the image acquired without film and *black_ref* being the image acquired with the light source off.

$$transmittances = \frac{raw\_image - black\_ref}{white\_ref - black\_ref} \qquad (6)$$

The images were then segmented and the pixels corresponding to the red, to the green and to the blue dyes were extracted. For each interference filter, three average transmittance values were calculated for the dyes.

The transmittance spectrum of the Dufaycolor film was also measured with the SHIMADZU UV-1800 spectrophotometer. In this case, the spectral range includes part of the IR and the UV, and the spectral resolution is considerably higher (down to 1 nm); however, it is not possible to measure the transmittance of the single colors. The area measured is in fact around 4 mm^2 and covers hundreds of patches of all the three dyes.

To verify the spectral accuracy of the measurements made with the interference filters, we compared the obtained spectra of the single dyes with the spectrum measured with the SHIMADZU (Figure 21 and Figure 22). To this aim, it was necessary to estimate the approximate area percentages occupied by the different colors. These percentages in the measured sample are 28% blue, 32% green and 40% red. The spectrum that takes into consideration the contribution of all the dyes was calculated from the spectra of the single dyes using equation (7).

$$\text{integral\_T\%} = 0.28\ \text{blue\_T\%} + 0.32\ \text{green\_T\%} + 0.40\ \text{red\_T\%} \tag{7}$$

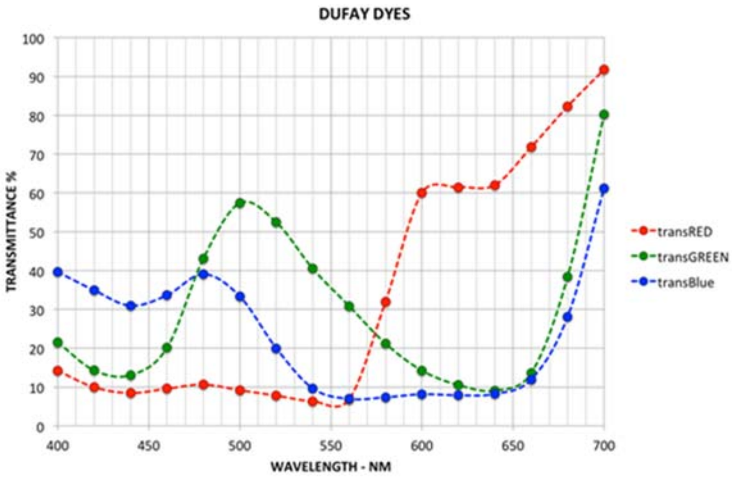


Figure 21 Resulting absorbance curves of the dyes in the tested Dufaycolor print

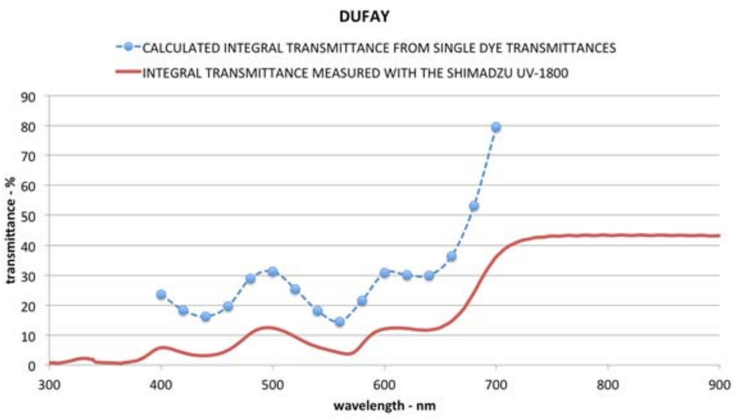


Figure 22 Integral spectral transmittance of the tested Dufaycolor sample

The two spectra actually correspond to two different areas of the film, and the different silver concentrations resulted in an offset of transmittance. However, the two spectra have the same trend and the peaks match quite well (Figure 22).

Even if a lower spectral resolution is achieved, in light of the successful comparison with the more precise bench spectrophotometer, the combination of the microscope with the interference filters must be considered the most effective measurement for the specific case, since it allows a direct measurement of the analytical densities.

3 Execution of Study, Observations and Questionnaire

As mentioned in the introduction, eight scanners were investigated at different facilities. During the testing, observations were noted and a questionnaire was filled out.

3.1 Abridged Overview of Scanner Models and Their Properties

Table 2 Overview of scanner models produced by the major scanner manufacturers. Models tested in this study are highlighted in red

Company	Model	Film Formats	Light Source	Sensor	Alternate visualization	Framing option
Sondor (CH), owned by DFT (D)/ Prasad (IN) since 2017	Altra HD	35mm, 16mm	LED	CMOS; 1920 x 1080 pixel; Bayer	Waveform, Histogram	Overscan
	Altra mk3	35mm, 16mm	LED	Kodak CCD; 2330 x 1750 pixel; Bayer	Waveform, Histogram	Overscan
Digital Vision (S/ UK)	Golden Eye	35mm, 16mm; 8mm, S8mm option	LED	Trilinear CCD; Non Bayer		
	Golden Eye 4	70mm, 65mm, 35mm, 28mm, 22mm, 17.5mm, 16mm, 9.5mm S8mm, 8mm	LED	Trilinear CCD; Non Bayer		
CIR (IT)	D-Archiver2 Cine10-A	35mm, 16mm; 8mm, S8mm, 9.5mm, 17.5mm option	LED	CCD; 2048 x 2048 pixel; Bayer	Histogram	Edge to edge
	D-Archiver2 Cine10-B	35mm, 16mm; 8mm, S8mm, 9.5mm, 17.5mm option	LED	CCD; 2336 x 1752 pixel; Bayer		Edge to edge
	D-Archiver2 Cine10-C	35mm, 16mm; 8mm, S8mm, 9.5mm, 17.5mm option	LED	5088 x 3840 pixel; Bayer		Edge to edge
DFT (D)/ Prasad (IN)	Scanity	35mm, 16mm, S8mm, 8mm	LED	3 mono-chromatic linear Dalsa CCDs; 4300 x 96 pixel; Non Bayer	Waveform, Histogram, Vectorscope	Overscan
	Scanity HDR	35mm, 16mm, S8mm, 8mm	LED	3 mono-chromatic linear Dalsa CCDs; 4300 x 96 pixel; Non Bayer		Overscan
Filmlight (UK)	Northlight 1	35mm, 16mm	HTI, LED option	Trilinear CCD; 6K; Non Bayer	None	
	Northlight 2	35mm, 16mm; 8mm, S8mm, 9.5mm option	HTI, LED option	Trilinear CCD; 8K; Non Bayer		Optional overscan gates
Kinetta (USA)	Kinetta	70mm, 65mm, 35mm, 28mm, 22mm, 17.5mm, 16mm, 9.5mm S8mm, 8mm; Microfilm, Paperprint option	LED	CCD; 4896 x 3264 pixel, other options; Bayer	Waveform	Edge to edge
Arri (D)	ARRISCAN 2K	35mm	LED	CMOS; 3K; Non Bayer	Histogram	Overscan
	ARRISCAN 4K	35mm, 16mm	LED	CMOS; 3K doubled by piezo micromovement; Non Bayer	Histogram	Overscan
	ARRISCAN XT		LED	CMOS (Alexa)		
Lasergraphics (USA)	The Director	35mm, 16mm	LED	CCD; 4K	Histogram, Waveform	Overscan
	Director 10K	35mm, 16mm, and 28mm, 17.5mm, 9.5mm, 8mm	LED	CMOS, 10K		Overscan
	ScanStation Personal	35mm; 28mm, 17.5mm, 16mm, 9.5mm, S8mm, 8mm option	LED	5K		Overscan
	ScanStation 5K	35mm, 16mm, S8mm, 8mm; 28mm, 17.5mm, 9.5mm option	LED	5K		Overscan
MWA Nova	Flashtransfer Choice	16mm, 9.5mm, S8mm, 8mm; 35mm, 28mm, 17.5mm option	LED	CCD; 2336 x 1750 or 5120 x 3840 pixel; Bayer	Waveform, Vectorscope	
	Flashtransfer Vario	35mm, 16mm	LED	HD; 2.3K, 2.5K, 5.1K; Bayer	Waveform, Vectorscope	

3.2 DFT Scanity

The Scanity by DFT is a scanner in operation at many facilities and in many archives (Figure 23). One of the main reasons for its widespread use are its speed and easy handling.

Figure 23 A part of the film path in DFT's Scanity. On the left side the film passes over the rounded gate. Source: DFT Scanity data sheet

First introduced in 2009 by the German company DFT, the Scanity is a capstan driven line scanner that comes with several options, a 35mm and a 16mm module plus a 2K and a 4K image processing option. In 2016 DFT announced an 8mm and wetgate option that is now available. Scanning speeds vary with resolution from 15 fps max at 4K, 25 fps max at 2K to 44 fps max at 1K.

> Illumination comes from the combination of discrete clusters of spectrally-separate red, green and blue LEDs. This allows accurate tailoring of the overall spectral power distribution to the density spectra of the emulsion layers, with a minimum of stray energy at unwanted wavelengths.
>
> A further refinement is that there are in fact two sets of red LEDs of slightly different center wavelengths; the appropriate set is used according to the type of film stock. After passing through an integration sphere, the light passes through the film via a very narrow slit and onto the sensors via a color beam splitter.
>
> (Scanity White Paper, pp. 7–8)

Thus the spectral characteristics of the red channels

- Red1 IMED/NEG: 660 nm
- Red2 PRINT: 690 nm
- Green: 530 nm
- Blue: 445 nm

are variable for specific emulsions, while there is a single spectral sensitivity available for the green and the blue channel.

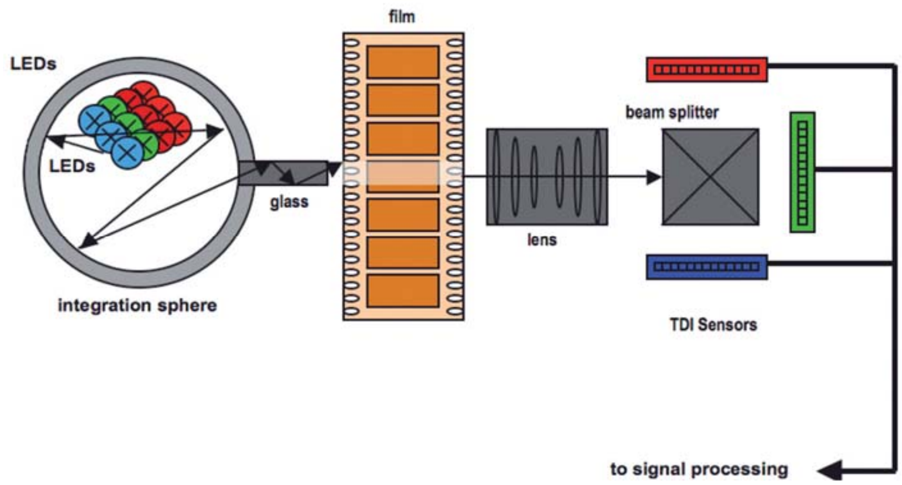


Figure 24 DFT Scanity light path. Source: DFT Scanity White Paper

The 4300 x 96 pixel layout of the sensor allows for scanning each line 96 times. This oversampling leads to the elimination of noise. Each line is processed by *Time Delay Integration* (TDI) line sensors (Dalsa) to deliver either DPX or TIFF files of up to 16 bit depth. Four sensors process the image information in R, G, B plus infrared channels by the use of a beam-splitter. The sprocket holes are registered by a dedicated camera. Based on the information, an on the fly image stabilization is applied. In addition to image scanning, the system provides soundtrack scanning of optical sound and digitization of magnetic tracks.

Scanity runs in the Linux environment. Focus is set automatically on grain, but can be adjusted manually. The mechanical layout of the scanner is fundamentally unsuited to scanning the full film width; however, the scanner enables an overscan including part of the perforation and the frame line. Through the control interface each channel R, G, B can be adjusted with an RGB waveform. There is also a preselection of settings available for certain more recent film stocks. Furthermore, settings can be imported from look-up tables. On the Scanity, positives need to be scanned from the side of the support layer due to the geometry of the gate where the optical sound track has to be positioned on the left side with regard to the running direction.

We did preliminary trials at EYE Filmmuseum in Amsterdam with restorer Annike Kross operating the Scanity. The first of two main investigatons on the Scanity were executed at Sound and Vision (Beeld and Geluid) in Hilversum by Paulo Veiga da Fonseca who is also a very experienced colorist and worked at Haghefilm Amsterdam before. A second investigation was done at Digimage in Joinville-le-Pont near Paris by technician Said Chaouni. Sound and Vision has only a 2K option on their machine, but both the 16mm and 35mm modules, while Digimage has a 4K option, but only the 35mm module. Both facilities have extensive experience in scanning historical film material, in the case of Sound and Vision from their own holdings, in the case of Digimage through restoration projects provided by customers, mostly from film archives.

Figure 25 Comparison of the Scanity scan at Sound and Vision (left, in 2K) to the one captured at Digimage (right, 4K)

In the comparison of two scans taken from the blue tinted film sample depicted above it becomes instantly visible that the two scanner operators followed different routes (Figure 25). While Paulo Veiga da Fonseca at Sound and Vision chose to capture the full tone range, Saïd Chaouni set the RGB waveform to more mid-tones.

As a result the two scans differ highly from each other. In both scans the blue tone in the perforation indicates that the blue hue is not really captured, but added by manual adjustment of the three channels, otherwise it would be white.

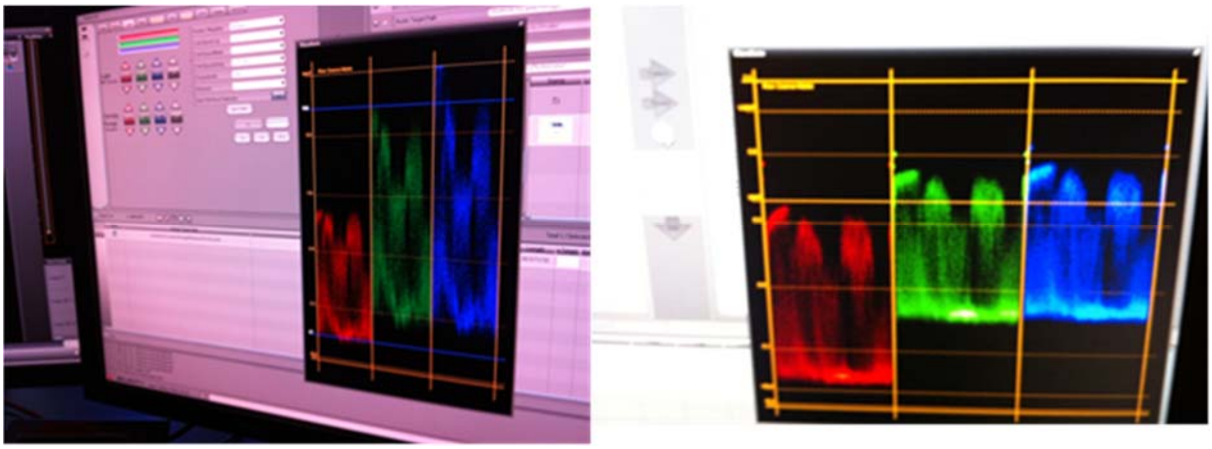


Figure 26 Comparison of the two RGB waveforms: Scanity at Sound and Vision (2K, left) and at Digimage (4K, right)

Due to its diagonal line screen Dufaycolor is a perfect material to study the influence of resolution on the result of the scanning. In the true to scale comparison depicted in Figure 27 the significant difference is visible. While the 2K scan delivers a good color impression, the réseau is blurred as a result of insufficient resolution. From a curatorial perspective it is required that the material properties of the film be captured as faithfully as possible.

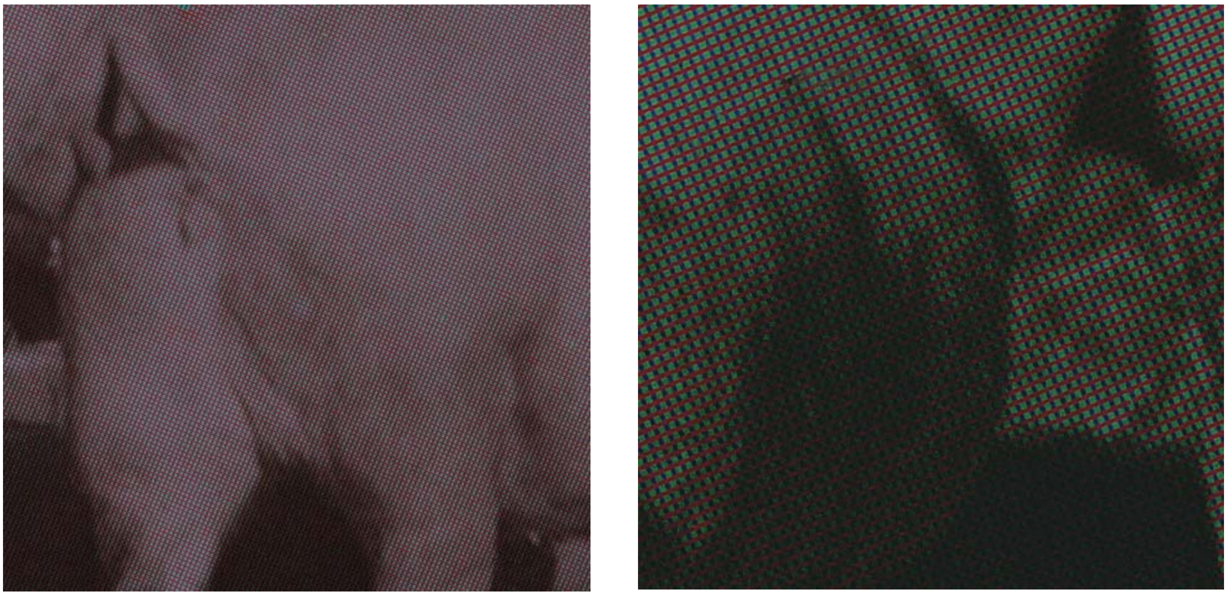


Figure 27 Influence of resolution on Dufaycolor: Scanity at Sound and Vision (2K, left) and Digimage (4K, right), true to scale

In the scans of Technicolor we noticed a greenish cast in all the samples captured at the three different locations. It is unclear where this stems from.

With regard to handling and practical operation the Scanity appears to be simple and fast. It was also easily adjustable to the non-standard position of the frame-line in the case of the blue tinted film. However, there are two considerable drawbacks resulting from the mechanical layout of the scanner. First, the stretch between the film reels and the camera is very long. This poses a problem for warped and brittle films. Second, the angles at the guide pulleys are narrow, which poses an additional threat to brittle and rare historical film material. As a result, EYE Filmmuseum, for example, did not process nitrate film at all in 2013, in particular not invaluable historical film elements. Since that time they have resumed scanning some nitrate film, but more as an exception than the rule.[20]

3.3 ARRISCAN

Among scanners, the ARRISCAN seems to be almost universally accepted as the most sophisticated scanner for archival film currently on the market. ARRI offers several archival options, a wetgate operated with Kodika SES Liquid, a sprocketless and pinless film transport.

The ARRISCAN has a native resolution of 3K that can be doubled by shifting the sensor four times half a pixel (see figure 15 in Kiening 2010) for captures to a 6K native resolution, which in turn is then downsampled to 4K. Additionally each frame can be captured twice by double flashes with successive narrow-band LED illumination in R, G, B (Red: 660 nm, Green: 540 nm, Blue: 450 nm) to improve signal-to-noise ratio (signal quality) in the first instance, resulting in a higher dynamic range (HDR).

[20] Personal message from Annike Kross, September 20, 2017

Figure 28 Operating the ARRISCAN via the control interface

Scanning speed is comparatively slow with 1.5 fps at 6K (two exposures for each color in HDR mode) and 5 fps at 3K (HDR mode). In addition to the RGB illumination there is an infrared channel for dust and scratch detection with a DICE option (Kodak). Scanning is processed frame by frame – either pin registered or with optical stabilization and captured with a CMOS sensor. The response of the sensor is related to the transmittance of the film. The RAW images can be output as 16 bit normalized TIFF or DPX files containing linear film transmittance data. The image content will not appear pleasing to the eye when viewed on a monitor at that stage because no gamma correction is applied to it yet. If the image originates from negative film it appears inverted (Figure 29).

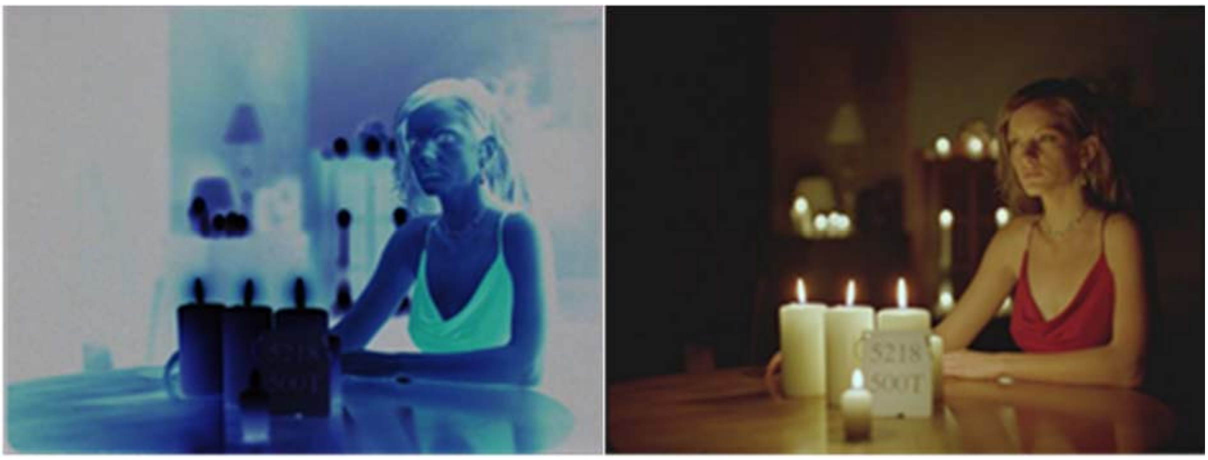


Figure 29 Example of a normalized image from a scan by the ARRISCAN (left) and after conversion using a LUT (right)

The following information was provided by Thilo Gottschling, Sales Manager Archive & Restoration at ARRI Media GmbH:

> The normalized image contains calibrated linear data which corresponds to the amount of light transmitted by the film. It is an accurate representation of the image on the film but not suited for the common DI postprocessing chain.

An output LUT is applied to the sensor code values to receive the final image. The LUT maps 16 bit integers (lin) to 16 bit integers (log) and for negative material inverts the image. If the selected final image file format has less than 16 bits, the result is truncated to deliver the desired bit depth (i.e. 8 or 10 bit).

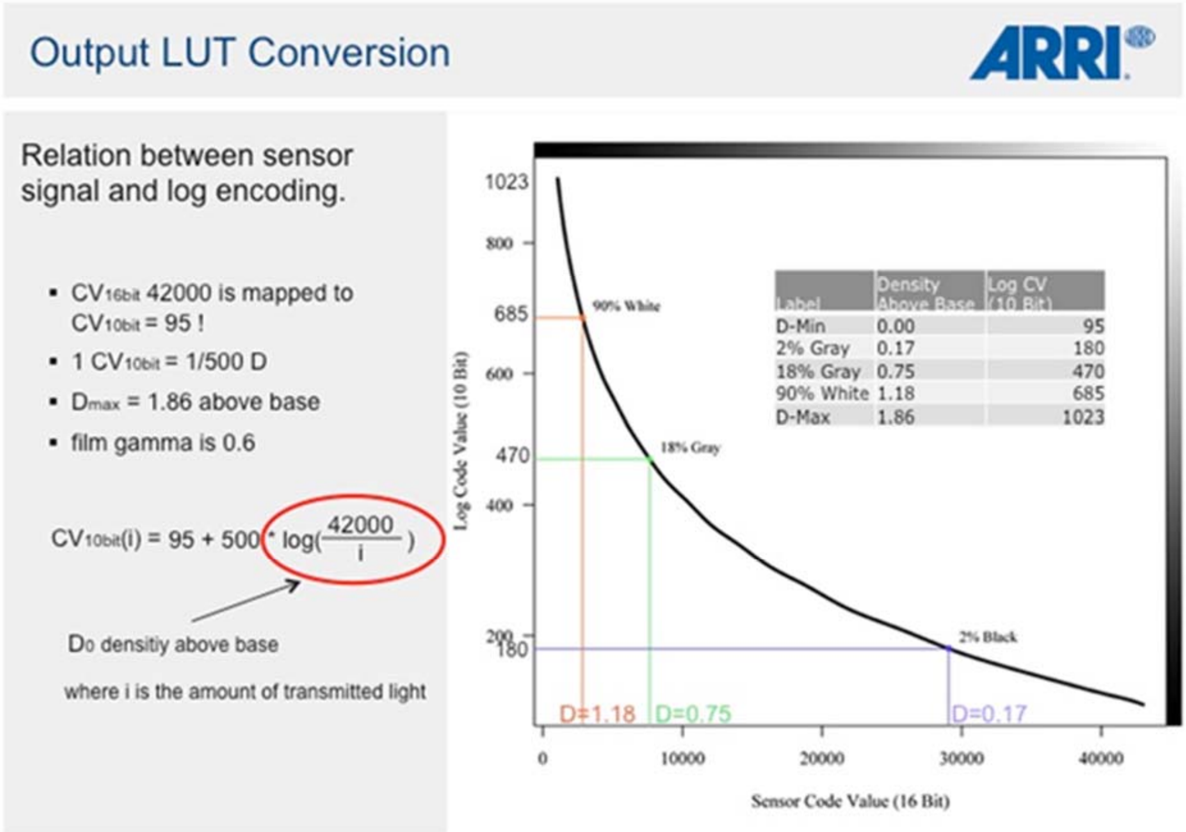


Figure 30 LUT conversion of 16 bit linear image data to 10 bit log (ARRI Archive Workshop, 23.06.2010)

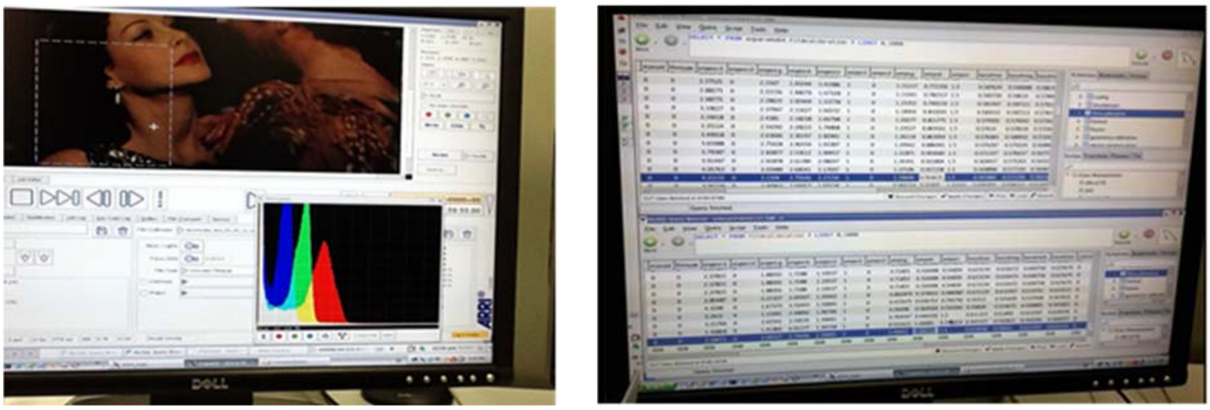


Figure 31 GUI of the ARRISCAN

Output formats are Cineon 10 bit log, DPX 10 bit log, 16 bit log, 16 bit lin or TIFF 16 bit and 8 bit (proxies only) files. The focus can be set automatically on the grain structure or adjusted manually. A calibration procedure has to be executed daily for the whole system. In addition, the scanner operator choses a region of interest (ROI) for each film material to set the operating point for the film scanner to a specific density or luminance, for instance to scan negatives with masking.

Image geometry can range from two to four perforations for 16mm, Super 16, and 35mm including full film width. A histogram as part of the GUI allows the scanner operator to adjust the levels in the three channels R, G, B (Figure 31). Settings can be stored and imported for certain "jobs". Depth-of-field is at times critical when thick splices occur. It depends on the distance of the lens to the film, and therefore on the image geometry chosen. Very experienced scanner operators can control the settings of the illumination directly in the controls table. The ARRISCAN does not provide scanning of any type of soundtrack.

We investigated the ARRISCAN at ARRI's facility in Munich with Sibylle Maier, Product Manager DI Systems at the time. Additionally, we spent a two-day workshop with Markus Mastaller at DIASTOR partner Cinegrell Postproduction's company in Zurich, where we repeated the scan of the Technicolor sample to figure out whether we could achieve better results with different settings and to work on improvements of the scanning of early applied colors as presented at the Colour Fantastic Conference at EYE Filmmuseum in March 2015 and published in 2018 (Flueckiger et al. 2018).

The ARRISCAN is certainly a demanding machine which requires a highly skilled operator. The film passes through the gate with tension adjusted through two open loops on either side of the camera block. Sensors adjust the height of the two loops and stop the machine if it exceeds a certain value, for instance when splices occur. The film tension is controlled by the software.

Figure 32 10 bit scan (left) vs. 16 bit scan (right) of the 16mm Ektachrome sample

The comparison of a 10 bit to a 16 bit scan (right) of the 16mm Ektachrome sample shows quite a pronounced difference to the 10 bit scan (left), which could be misleading (Figure 32). In fact, the tone range of the 16 bit scan is as expected higher, but requires the adjustment through a specific LUT or pre-grading, as mentioned before.

In general, however, the ARRISCAN shows some problems in processing very dense film stock. This problem became obvious especially with the Technicolor sample (Figure 33).

Figure 33 Technicolor sample scanned at 16 bits per channel before (left) and after (right) color correction by colorist Timo Inderfurth

In color grading it was possible to retrieve a high range of information that on first visual inspection seemed to be lost. At DIASTOR partner Cinegrell Postproduction's color grading suite, colorist Timo Inderfurth adjusted the scan to the projected film image; see information about this process in the chapter *Subjective Evaluation and Results*.

Figure 34 The réseau of the Dufaycolor sample as shown on the control monitor

Thanks to the discrete processing of the color channels and the very good color separation in combination with its high resolution and the omission of debayering in ARRISCAN's optical set-up, Dufaycolor was captured at 4K with the réseau in full resolution and every detail of the color filters, even when captured from the monitor. Results were also very good with faded chromogenic stock when the scanner was calibrated to black.

140 ARRISCANs were sold; about 80 to 100 are in operation. Currently about five machines are produced per year. Maintenance costs depend on the service agreement.

3.4 Kinetta

The Kinetta scanner (Figure 35) is one of the very few that were developed from the start to fit the needs of archival films. The original Kinetta was designed in 2005 for the Library of Congress to scan paper prints. Designer Jeff Kreines has several decades of experience in handling historical film stock. The scanner has evolved through several generations since then, adding features and improving quality. Earlier versions of the Kinetta can be refurbished to take advantage of recent developments.

Unlike most other scanners, the Kinetta is a flatbed scanner designed modularly. The latest generation has a resolution of 4.8 k with a Bayer CCD sensor. The sensor module is interchangeable – and can be swapped out. This means that the Kinetta can always be upgraded as better or faster sensors become available.

It operates at continuous, capstan driven transport with diffuse LED, pulsed RGB and white, illumination.

Figure 35 The Kinetta scanner at Jeff Kreines' facility

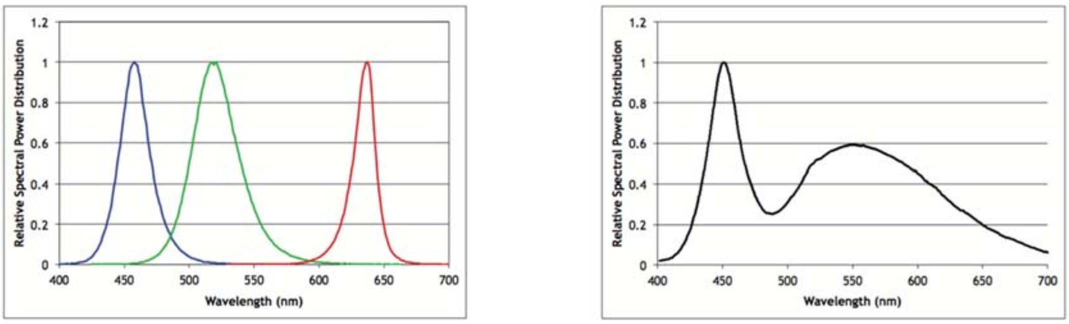


Figure 36 Spectral characteristics of single red, green and blue LED light sources and the white LED light source (right) of the Kinetta scanner

Color balance and intensity are adjustable on the monitor controls. The user has complete control over the color balance of R, G, B, and white LED light, as well as the pulse width of the single light flash.

In addition, adjustments for gamma, shadows, midtones, highlights, contrast, and more can be made. The polarity of the image can be changed for scanning negatives, and the image can be flipped horizontally and vertically as needed. The film can be scanned in either direction, from head-to-tail or tail-to-head.

Resolution and scanning speed are dependent on the camera module. The 4.8k scanning speed is up to 12 fps, while lower resolution versions offer real time scanning and faster frame rates. Unlike other scanners, the Kinetta does not allow for down-sampling during capture; this has to be done in post-production. Current output formats are 16 bit Cineform RAW and 16 bit CinemaDNG RAW. While DPX is supported, it would require an extremely fast RAID to capture 4.8K at 12 fps. According to his feedback, Jeff Kreines is considering support for FFV1. He uses the software FFmpeg for the output formats conversion. Therefore, he can adopt any of its offered/inherent codecs.

At the moment Kreines prefers the 16 bit Cineform RAW format for 16 bit data processing. The older Kinetta model, investigated at Reto Kromer's facility – which has since been updated – lacked real-time stabilization. The new Kinetta does offer optical stabilization based on processing the recorded images of the perforations. It is no longer dependent on mechanical adjustments other than setting the appropriate tension for the film being scanned, regardless of whether the film is warped, brittle, or otherwise damaged.

With regard to formats, the Kinetta is by far the most versatile of all scanners investigated. It processes 35mm 2, 3, 4 perf, 35/32mm, 28mm, 22mm, 17.5mm, 16mm, Super 16, and amateur formats such as 9.5mm, S8mm, Super 8, and 8mm. There are options for microfilm and paper print, and others are available on request. Image geometry can be adjusted by the selection of different lenses and adjustment of the distance between the lens and the film strip. It allows the capturing of the full film width, which is very crucial for archival films. There is a detailed GUI which offers many control possibilities but needs some experience to adjust properly despite the fact that the scanner is generally very easy to operate (Figure 37). The scanner's operating system is Windows 7.

Figure 37 GUI of the Kinetta scanner

Kinetta offers the option to extract a rough sound file from the scanned image that is automatically synced to the film. The controls allow the operator to adjust tension, exposure, all the different illumination parameters, and a preselection of stocks (positive and negative). A histogram is provided on a second UHD monitor that also allows the visual inspection of the scans. Focus is set manually. The scanner weighs around 65 pounds and is in principle portable in a transport case.

We first investigated a Kinetta scanner at Reto Kromer's facility AV Preservation by reto.ch in Ecublens, Switzerland. The scanner was newly delivered and showed some problems, especially with the operating system. Jeff Kreines operated the scanner himself. In June 2016 we repeated the study on the latest model at the Film-Makers' Cooperative in New York, again with Jeff Kreines as operator.

In general, the Kinetta showed the least problems with scanning dense positives. In particular, the dynamic range in the very dense Technicolor print did not pose a problem to the scanner. The highlights still contained detail after the black level was set.

Figure 38 Technicolor sample scan from the Kinetta before (left) and after (right) color correction by colorist Timo Inderfurth

Thanks to the very good dynamic range of the scan, color grading with reference to the projected film was quite easy for colorist Timo Inderfurth (Figure 38).

The most obvious problems arose in the Dufaycolor scan. The réseau was highly pixellated, probably due to debayering, despite the high resolution of almost 5K (Figure 39).

Figure 39 An excerpt of a Dufaycolor frame, scanned on the Kinetta

As mentioned above, the Kinetta had difficulties to process and stabilize the very short blue tinted fragment with its non-standard frameline located at the center of the sprocket holes instead of between them (Figure 40). According to the manufacturer, the new version of the Kinetta resolves this problem: "Now triggering is done in a hybrid manner, using both the perf sensor and a very high resolution encoder, so missed perf triggers don't cause any problems, even long stretches of no perforations at all."

Figure 40 Problems adjusting to the non-standard frameline of the very short blue tinted fragment

In 2016 there were 17 Kinettas in use. Maintenance-wise, the first year is covered by a full parts, labor, and software/firmware upgrades. Kinetta offers a maintenance agreement for the second year, onward, for about 9% of the purchase price per year.

A severe limitation is the variable availability of the scanner manufacturer for support and amendments. So far most maintenance has been handled via email and TeamViewer. The Kinetta staff log on to the user's computer to upgrade software and firmware. If any parts need to be replaced, Kinetta ships with FedEx and guides the user through replacement.

3.5 Altra mk3 by Sondor

Sondor was founded in 1952 and became internationally known for their sound equipment for film production. They have a long history producing a wide range of machines for audio recording and postproduction for broadcast and motion picture use. In the early 1970s, the company widened their spectrum of products with a studio film projector and an SD telecine. The company's first scanner model, the Altra HD, a real time high definition scanner with SD- and HD-SDI as well as composite and component outputs was introduced in 2007. DIASTOR ran their film samples on the newest model, the Altra mk3, which scans in 2K with the Kodak KAI CCD sensor at a resolution of 2330 x 1750 pixels via a Basler Aviator camera head. The debayering is done on the graphics board of a Windows workstation shipped with the scanner.

Sondor's background in the mechanical aspects of film transport provides a solid base for their scanner production. For capturing and image processing they collaborated with Marquise Technologies in Gland, Switzerland and the Digital Humanities Lab of the University of Basel.

Figure 41 The Sondor Altre mk3 is built in a standard 19” rack geometry and through its modularity offers the addition of a wide range of sound heads into the film path

The Sondor Altra mk3 is not aimed at restorers dealing with film in a critical condition, but it offers a series of options geared towards the archival market. One of its main features is its real time scanning speed in 2K, which allows for rapid scanning. Quick shuttling with a preview image facilitates navigation within a reel. For scanning the speed can also be reduced below real time if necessary to handle more delicate material, but it is not recommended to digitize the soundtrack at reduced speeds because it can only be accurately recorded in full quality in real time playback. The curved gate, tension adjustment possibilities and sprocket design are laid out for dealing with older and shrunken film. A five step echeloned settings option that manages tension, top shuttle speed and film acceleration helps to accommodate different film conditions. The sprocket driven mechanism offers easy exchange routines between 35mm and 16mm formats; sets of sprocket wheels are also available with reduced pitch for shrunken material. A sprocket wheel reduced in size by 0.5% (all dimensions, not only the teeth) can take up to 2% shrunken material while a wheel reduced by 1.5% will allow for up to 4% of shrinkage. Andrea Braun, Sondor's chief service engineer and our operator for the study, explained that sprocket driving of film has disadvantages for highly damaged and fragile film but is preferable in keeping the tension on the film lower than with the capstan drive solution. According to Braun, Sondor’s experience with shrunken and warped film has been very positive.

The Altra mk3 has an upright frame based on the standard 19” rack geometry, with the feed reel on the top and the take up reel on the bottom, both in vertical position. To help with badly wound or warped film which tends not to spool regularly there are optional split spools to hold the film in place safely on the feed and the pick-up side. The distance for the film to pass through is rather long and the angles around some of the pulleys are quite narrow. The whole machine follows a modular concept, with numerous sound options. Sondor offers a choice of all standard optical and magnetic sound heads for 16mm and 35mm film, including mono and stereo red LED, mono single track tungsten, Dolby Digital, DTS timecode reader and Sepmag and Commag formats for 35mm as well as mono optical red LED, Sepmag and Commag readers for 16mm. Sondor's unique experience is apparent with regard to soundtrack transfer to digital. Their closed loop sound heads mechanically isolate the sound pickup from interference, for example due to bad splices. The optical sound heads allow manual adjustment of the azimuth as well as the track's position to obtain best possible results. In the magnetic head-stack the film runs through a special guiding system just in front of the pickup and pinch rollers to ensure that the head and the track are in tight contact. Heavily shrunken and warped material can still be scanned with good results.

Under the brand Versa, Sondor offers a completely flexible system. In a transfer machine all of Sondor's sound technologies can be combined as the customer prefers. This includes Sondor's Resonances optical soundtrack scanner. Resonances scans optical soundtracks as image data and conducts an image based digital restoration in real time to remove dust and defects. Only then is the image converted to audio, delivering a much cleaner sound than traditional methods. This system avoids a lot of noise and artifacts in the digitized sound and thus makes digital audio restoration much easier.

The Altra mk3 runs continuously. Images are captured by flashing an RGB LED light source at 617 nm, 529 nm and 460 nm. The focus can be adjusted automatically or manually. The gate is curved and has a counter gate so even warped film lies flat. Combined with the depth of field offered by the optics, the focus is maintained well over the whole area of the image. The area of the film to be scanned can be chosen by mechanically shifting the optics unit. Due to the construction of the gate the film cannot be scanned edge to edge, but it has an overscan area partially showing the perforation. The image can be recorded flipped horizontally and vertically, and scanning backwards is possible.

Output data formats are 10 bit DPX and 12 bit DNG raw format, TIFF, TARGA, QuickTime and optional JPEG2000 in MXF and DCP container formats.

The machine’s well-structured GUI, which was developed in collaboration with Marquise Technologies, shows a preview of the scan and histograms to help judge the image quality. There are options for an automated and a manual color balance procedure. Color information can be read from any point of the scanned image with a color picker tool. When a spot representing a grey image point is chosen, the RGB values can be adjusted with the help of the histograms to receive a neutral grey. This manipulation changes the light intensity of the separate red, green and blue LEDs in the light source. The dynamic of the image is adjustable by an "exposure" value which manipulates the duration of a single flash. The increase of the flash duration has an upper limit due to the continuous movement of the film. A range of 5 to 63 microseconds is available. Further adjustments to the black level as well as the gamma can be made. In the group of the DIASTOR film samples used there was an issue with the automatic color balance procedure on the Kodachrome sample. The image would turn out too dark and the setting needed manual correction. Other materials with high densities, like the Technicolor sample, did not show similar behavior. During the scope of our investigation we did not determine the cause of this issue. It is clear in any event that exotic color systems tend to require manual control of the available parameters.

Given its manufacturer’s history, it is no surprise that the Altra mk3 offers by far the best options for digitizing motion picture soundtracks of the group of scanners investigated. For image quality, it is in the midrange. Naturally the limitation to 2K resolution shows in comparison with higher resolved scans even if compared in a 2K projection. This is most visible for the Dufaycolor sample where just 2K will not properly resolve the structure of the material. An additional factor could also be the debayering process which further lowers the sharpness of structures at the edge of the given resolution.

The reversible 16mm film stocks turned out a bit weak in color. Their natural look of intense colors was not reproduced as well as in other scanners' results. As with most other machines investigated, the Kodachrome sample we provided posed a huge challenge in reproducing details in its densest and lightest areas. Nevertheless, the results were good for the Technicolor sample with its densities far greater than those of a regular chromogenic film print.

Figure 42 Sondor Altra mk3: Rendition of Kodachrome with manually adjusted contrast

Generally the scanning session took much less time to complete compared to other ones. This fact and the image results reflect that Andrea Braun was a technician who knows the machine in detail but he is not a grader or specialist on historical film colors.

Currently there are 28 of Sondor's scanners in use, nine of which are Altra mk3 models. At the time of the investigation it was not possible to save settings, but this feature was made available in spring 2016. Five presets can be saved and activated via the GUI. Any further presets can be stored to the hard disk as XML files.

The Altra mk3 is synced to a digital audio clock to ensure steady sound recording. It is also possible to feed in an external clock signal.

As of January 2017, the Sondor Company has been aquired by Digital Film Technology GmbH, through which Sondor's products and services are now available. The Altra mk3 is no longer produced and has been replaced by the model *Versa* which combines Altra mk3's features with that of the optical soundtrack scanner *Resonances*.

3.6 Northlight 1 by Filmlight

The Northlight is a scanner produced by the British company Filmlight. The machine used for scanning the samples was a Northlight 1 at DIASTOR partner Cinegrell Postproduction in Zurich, Switzerland. Filmlight states on their website that Northlight 1, introduced in 2005, has been sold to 40 postproduction companies worldwide.

Northlight 1 scans 35mm including 2perf, 3perf and Vistavision as well as 16mm and Super 16 film formats in up to 6K native resolution using down-sampling to 4K or 2K. It is a flatbed scanner and the hardware change between 35mm and 16mm is simple and can be done within a few minutes. The film path is reasonably short with no sharp turns. The automatic film tension handles the film with care. Film tension cannot be set manually.

At 4.7 seconds per frame for 35mm at 4K and 2.6 seconds in 2K the Northlight 1 is a relatively slow machine. Speed has been significantly improved on the later model called Northlight 2 to 0.8 seconds per frame for 35mm in 4K and 0.5 seconds per frame for 2K. The film transport relies on sprocket wheels. Line scanning is done frame by frame with pin registration. Scanning with pin registration is cumbersome for dry and shrunken 16mm film, because the scan often aborts automatically. For such difficult cases the pin registration can be deactivated. This results in lesser image stability which can be addressed with software tools at a later point.

Figure 43 Problems adjusting to the non-standard image geometry of the blue tinted fragment on the Northlight 1 scanner (color corrected scan)

Overscan options are very limited. It is impossible to scan the sprocket area of the film; the tinted sample with its non-standard frame line could not be scanned in a way capturing the whole image correctly.

The focus cannot be adjusted manually, neither in the GUI nor mechanically. The staff at Cinegrell was able to access some special functions on a command line level but no such procedure was known for the manual setting of the focus. Like most scanners, the Northlight 1 was not conceived for archival use and offers limited options and workarounds for these needs.

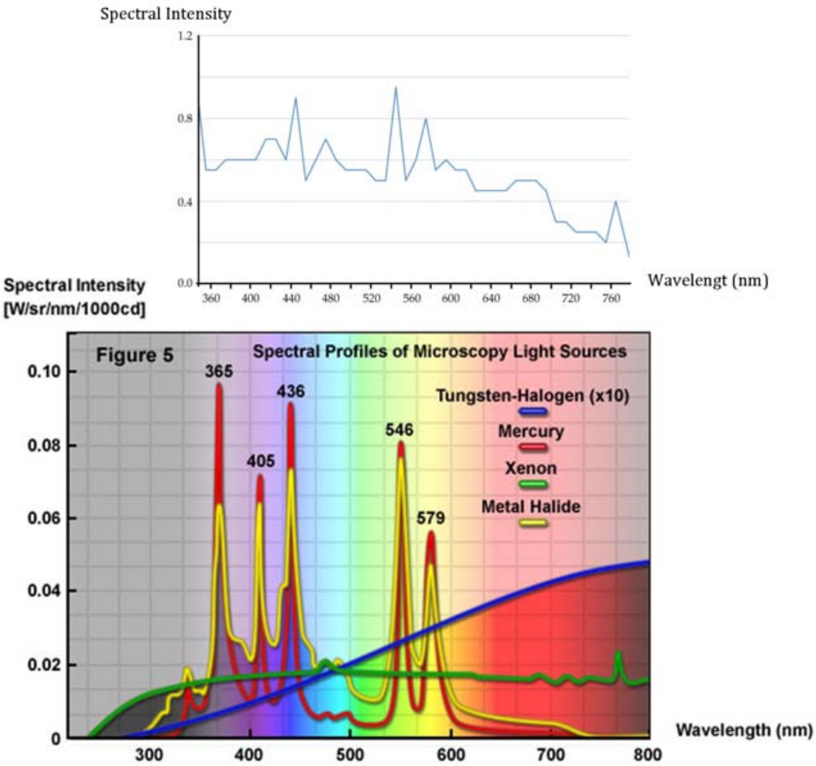


Figure 44 Comparison of the spectral characteristics plot received by Filmlight with a chart of the common light sources tungsten-halogen, mercury, xenon and metal halide. Source: http://zeiss-campus.magnet.fsu.edu/articles/lightsources/lightsourcefundamentals.html

Northlight 1 uses a diffuse broadband HTI light source but the light striking the film is limited to three bands at wavelength regions of 380 to 480 nm, 520 to 580 nm and 620 to 680 nm by an MSO filter, which limits the influence of spectral sidebands of the dyes.

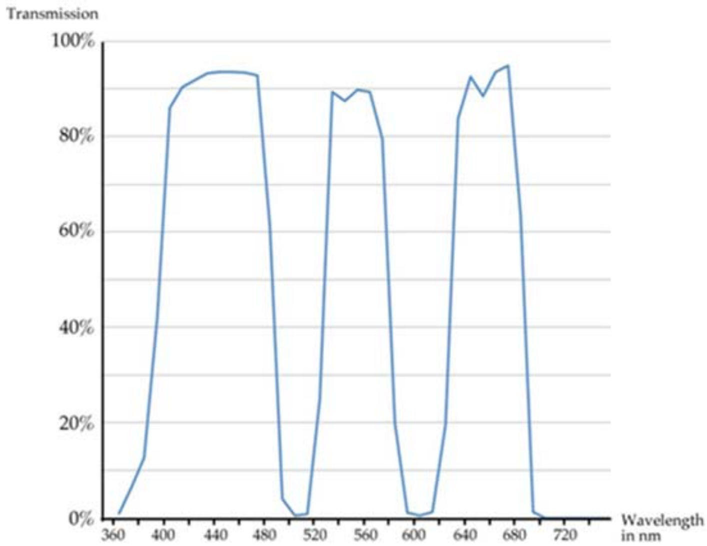


Figure 45 Transmission spectrum of the MSO filter in the Northlight 1 scanner

Northlight 1 is a step scanner with a line sensor. The film image is positioned by the pin registration and held steady in the gate for scanning while the whole gate assembly travels between the mechanically fixed light source and the Truesense KLI-8023 CCD line sensor. The signal coming from this trilinear color sensor is then computed to render the scanned image. Filmlight offers an alternative LED light source which was not available to DIASTOR for our study. An additional scan per frame with infrared light is optional to create a scratch and dust map for later processing.

Colors are read at 16 bit per channel and converted to the output file format's bit depths. The choice of film formats are DPX at 10 bit and TIFF at 8 or 16 bit.

There are no options for scanning soundtracks.

Linux is the machine's underlying operating system. Most controls are executed through a GUI, apart from some special functions which can be invoked through command line processing. The GUI is not very clearly laid out and some nomenclature is a bit unfortunate or cryptic. To scan print material, for example, the option "Interpositive" must be selected under "Stock" while the option "Print" is found under "Color Space".

There is a window showing the last scanned image, but no further visual tools are provided for navigation in the immediate or broader range around the image positioned in the gate. Thus navigation within the film reel can pose a problem. It is also impossible to zoom into the preview image.

Settings cannot be saved to a file, but a summary of the current settings is continuously shown at the top of the GUI for quick reference.

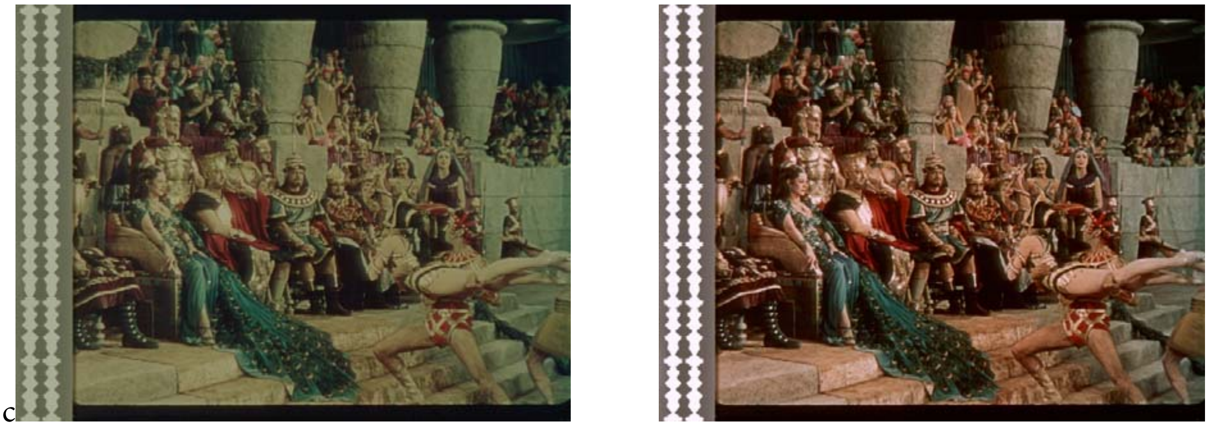
An interesting and flexible tool is the setting of the so-called "exposure offset". One might speak of a calibration procedure but that term is already occupied by another function that must be executed when initializing the basic setup like film format, resolution and film stock. What this calibration procedure exactly does is not clear to the user. The exposure offset is basically a tool to set the black point of the image material used. This can be done automatically using the frame line, or manually by the user picking a point within the image or from any area of an overscan image. Alternatively any other point can be defined as middle grey or the white point. The exposure offsets calculated this way can be further adjusted manually with three separate sliders for red, green and blue. There are no other color grading options and no alternative visualizations such as a histogram. The minimal options for intervention are a double-edged sword. Scans should be an optimal record of the information stored in the film material with no unduly strong grading efforts executed during scanning; on the other hand, the limited options may be a problem when scanning historical film colors which need manual adjustments by the experienced user to give appropriate results.

On Filmlight's follow-up model Northlight 2 significant changes were made compared to Northlight 1. The improvements include a completely redesigned gate, more options for different film formats including 8mm, a native scanning resolution of 8K for an oversampled 4K output, significantly faster scanning at all resolutions and additional options in the GUI. Northlight 2 is obviously much more geared towards the archival market than its predecessor. It features the redesigned gate which offers registration pins for film with up to 3% of shrinkage as well as pinless scanning. The pinless gate also allows to scan more than the image area (overscan). It captures a part of the sprocket holes. The sprocket drive can be replaced by a capstan movement if desired. Also an option to set the focus manually has been introduced. Generally more manual control can be executed to facilitate the scanning of delicate and damaged material.

Northlight 1 and 2 use an HTI metal halide light source; both models can be updated with a LED light source on request.

David Pfluger of the DIASTOR team scanned the film samples. He was introduced to the machine by Cinegrell's Michael Egli and was in contact with Wolfgang Lempp of Filmlight, who provided technical information on the scanner's light source.

The results with Technicolor material on the Northlight 1 were very good (Figure 46). Unlike other machines that struggled with the high densities of the material, a good range of densities was achieved.



c

Figure 46 The Northlight 1 Technicolor scan ungraded (left) vs. the color-corrected version (right)

The tinted sample, on the other hand, caused problems due to its non-standard frame line, and the intense blue tint was completely invisible to the scanner, which delivered a black and white image (Figure 47). This is a surprising result considering the broadband light source of the machine. The problem even persisted when the MSO filter was removed. No straightforward explanation could be found.

Figure 47 Northlight 1 scan of the blue-tinted fragment

Overall, the results of the scans with the Northlight 1 scanner are in the mid-level of the group of devices tested which represents well the combination of the machine’s limitations relating to non-standard samples and the scanner operator’s limited experience with the settings options. Generally, the color balance was set by using the automatic exposure offset procedure picking the darkest point from the frame line where possible and otherwise from the exposed film image itself. This strategy seemed to work well for the chromogenic materials and the Technicolor sample. A slight greenish hue in the results could be removed in subsequent grading.

3.7 The Director by Lasergraphics

The Director is a scanner built by the US company Lasergraphics and was introduced to the market in 2007. Lasergraphics' scanners are well represented at major US institutions like the Library of Congress and Warner Brothers and French institutions including the Institut National de l’Audiovisuel INA and Centre national du cinéma et de l’image animée CNC.

The Director is able to scan 35mm film including 2perf and 3perf as well as 16mm and Super16 film formats in up to 4K. At 3 frames per second for 35mm at full aperture in 4K, it is relatively fast.

Interchanging the setup between 35mm and 16mm is not a complex procedure; at the same time, however, the whole gate along with the film transport wheels and the pulleys need to be exchanged as part of one big unit which is quite heavy to lift.

The film is driven by sprocket wheels which allow up to 2% material shrinkage of the material. As with the Scanity, the distance between the reels and the gate is long and the angles around the guide pulleys are narrow, a design that is not well suited for films that have undergone decay.

The Director is a step scanner using an optical system for image stability (“optical pin-registration”). By detecting the horizontal and the vertical edge of the perforation it can stabilize the image in both directions. When an image is scanned the film is pressed down along all four sides by a pressure plate. Its gate is oversized, partially revealing the sprocket holes, but the system prohibits scanning of the complete film width. The image area to be scanned can be chosen manually by drawing a square in the full sized preview image. This is an interesting feature, but images with non-standard aspect ratios can require additional efforts further down the line in the workflow.

Equipped with a highly diffuse LED light source The Director offers HDR scanning with double or triple flash at different light intensities (Figure 48). This is an advantage when scanning high contrast film like positive prints, reversal material and Technicolor prints. For the study the triple flash option was chosen because many of the sample materials showed high densities (bw reversal, Kodachrome, Technicolor, tinted positive).

However, when investigated the scanner proved to have difficulties capturing very dense materials, despite the multiple exposures.

Optical soundtrack readers are available and the sound can be read and output in sync to the image as a ProRes file.

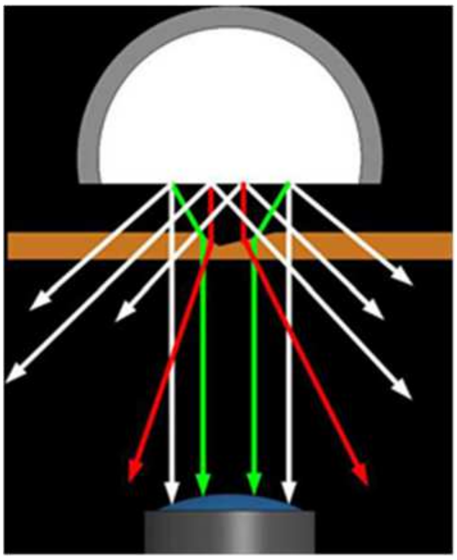


Figure 48 Simplified diagram of the light path from the diffuse light source of The Director through the film into the optics of the sensor

Figure 49 HDR scan of the Technicolor sample by Lasergraphics in 2K at 10 bit (left) and in 4K at 10 bit (right)

The work was conducted at the Institut Nationale de l'Audiovisuel INA in Paris, France. David Pfluger of the DIASTOR team visited the INA together with Jeff Ferriol of Magic Hour, who is a representative of Lasergraphics in France and had arranged to make the tests possible. The scans were executed by Jean-Yves Baudon of the INA's Cadre Technique.

Mechanically the material posed no problems. The shrunken historical samples ran through the machine flawlessly. Using the preview image and the thumbnail preview, navigating through the film reel was easy. The well-structured GUI offered a good overview of the current settings and processing (Figure 50). It is possible to save the settings made in a session. The GUI running on a Microsoft Windows machine is well conceived and there is an additional small screen built into the housing of the scanner which helps to keep an overview when standing at the machine. There is no way to increase their size on the display.

Figure 50 GUI of The Director scanner by Lasergraphics

A focus calibration procedure is executed at the beginning of each session. There is an option to set the focus manually. The operator Jean-Yves Baudon considered a manual setting of the focus unnecessary as there had never been a problem with it. This is representative of the fact that a lot of material, including older films, that are scanned with the machine at INA all belong to a rather narrow choice of film stock. Films scanned at INA are mainly newsreels footage on black and white and modern chromogenic film stock and include minimal early or rare material. In consequence, the scanning results became less solid and took longer to carry out when we used materials with which the operator lacked experience. As with the Northlight 1 scanner, the tinted piece of film appeared almost completely black and white; the black and white densities were excellent, but nonetheless without color (Figure 51).

Figure 51 Uncorrected capture of the blue tinting by The Director scanner by Lasergraphics in 2K at 10 bit, adjusted to the non-standard frame position (left); adjusted to dial in the blue tinting by offsetting the calibration which results in a pink hue in the perforation area (right)

The option for uncompressed output image file formats are 10 and 16 bit DPX and 8 and 16 bit TIFF. The machine offers various other compressed output file formats. We first chose 16 bit TIFFs, but the images scanned proved to have a strange blue hue and could not be used. After fruitless efforts to try to find the cause for the issue, we settled for 10 bit DPX files.

Similar to other scanners, the machine and operator performed excellently within the context of familiar tasks but encountered difficulties with unfamiliar material. Producing a good result in this case took significantly more time or proved impossible.

There is an option to record a detect map for dust and scratches but it was not used.

3.8 D-Archiver Cine10-A by RTI

CIR is a company well known for their precision film splicers. They are based in the vicinity of Rome in Italy and have years of experience with tools used in film labs for darkroom purposes and quality control. The company is owned by the US-based company RTI Co. In addition to producing rewinding and inspection tables, CIR started to build models using digital cameras to magnify the image for film inspection, extending the features up to a full scale flatbed scanner, the D-Archiver (Figure 52). Several submodels of the D-Archiver are available: The Cine10-A, the New Frontier Cine10-B and the Cine10-C.

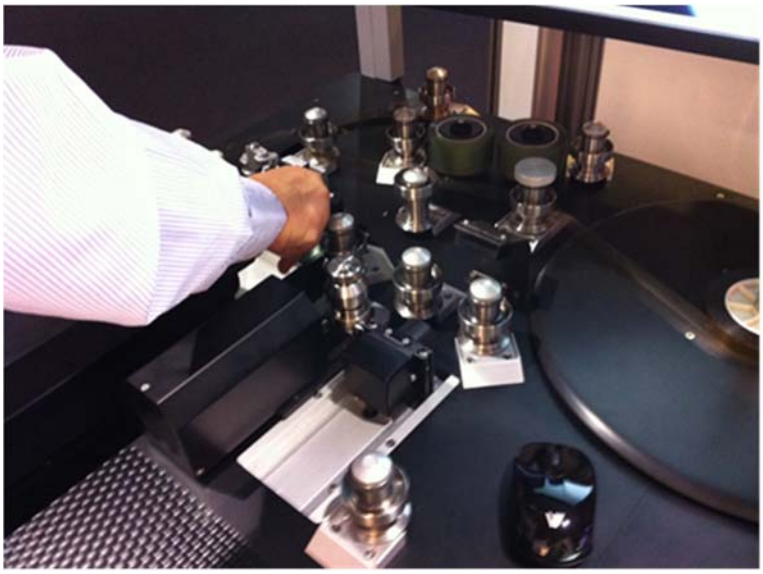


Figure 52 RTI's D-Archiver Cine10-A built by CIR

While it does not abandon the inspection table feature, the D-Archiver still has a light box, an analogue video output and the overall appearance of an inspection table. The light box and the "table arrangement" also proved helpful for navigation in the close range around the images scanned (Figure 53).

Built as a modular system, the scanner offers many optional features. Apart from basic 35mm and 16mm film formats it can be updated to small gauge formats like 8mm, Super 8, 9.5mm and 17.5mm. Variable rollers fitting several film widths reduce the efforts needed to change between the different film formats. Other additional features include special archival gates, a "scratch finder" unit plus optical and magnetic sound heads. The scratch finder is an IR LED and CCIR camera unit working at a 950 nm wavelength. Physical defects like scratches can be detected as well as defects due to chemical decomposition.

Figure 53 The diffuse flashing LED light source of the D-Archiver Cine10-A and the camera unit (covered)

Another interesting feature is the possibility to adjust the level of diffuseness of the light source with a set of diffusion filters. This is a feature that probably no other machine offers and is a new field where experience still needs to be gathered on a larger scale. The light source is a 4300K LED array flashing for the image transfer to the Kodak 2048 x 2048 CCD KAI sensor while the film is in continuous motion. The square layout of the sensor results in scans covering much more than the height of a single film frame and thus offers a high flexibility on the vertical positioning of the scan area. The brightness of the image is set manually via the diaphragm in the lens. The gates are built so the whole width of the film can be recorded, also facilitating inspection of the perforation area. The maximum resolution for the Cine 10-A machine which we were using is 2K, with a scanning speed of up to 7 fps for the highest resolution and bit depth. An interesting feature is that the images can be scanned as RAW data at 16 bit. Based on this data it is possible to render out different image file formats like DPX 10 bit or 16 bit and TIFF or compressed preview clips in lower resolution. This process leaves open the decision on the final data format until after the scanning process and multiple data formats can be rendered out. The audio is played out as a WAV file.

The newer model, the D-Archiver New Frontier Cine10-B, allows real time scanning in 2K with 2336 x 1752 pixels at 12 bits. The Cine10-C scanning at 12 fps in 5K (5088 x 3840 pixels) is available as well.

The image stability is controlled via a passive sprocket wheel. These are the only sprockets in the film path and can be adapted to shrunken film by a pitch control adjustment. The tension on the film can be adjusted as well to suit more fragile film. It is possible to scan forward and backwards.

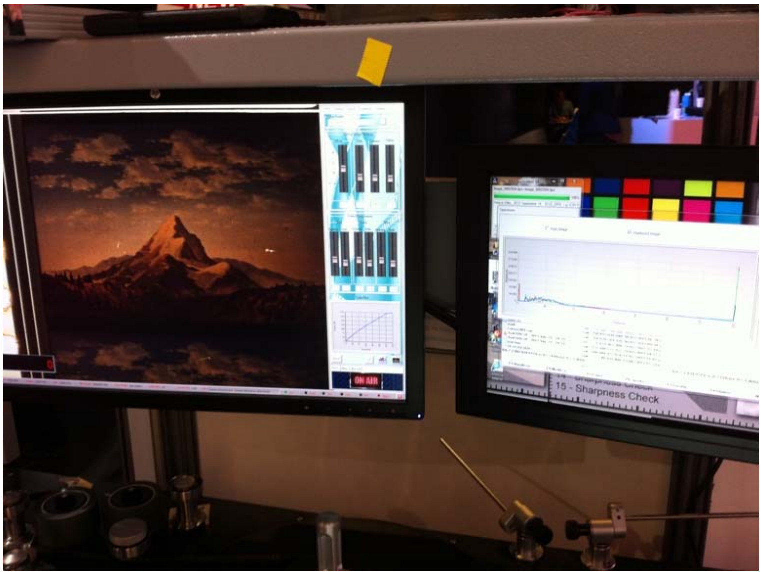


Figure 54 GUI and control monitors of the D-Archiver Cine10-A

The machine is equipped with two screens and a smaller touch screen integrated in the surface of the table (Figure 54). The larger screen shows the preview image and the GUI to its side, the other shows the infrared image taken by the scratch finder. The touch screen gives an overview of the current settings and indicates the actual scanning speed and amount of film scanned. The GUI offers basic settings like color saturation, offset, gain and gamma as well as corrections on the separate color channels R, G and B. Emulsion choices are negative, intermediates, positive and reversal.

The focus and the choice of image section to be scanned are adjusted manually, directly on the lens. The settings are made in part purely mechanically. The settings of the light diffuser and the focus, for example, cannot be saved to a file.

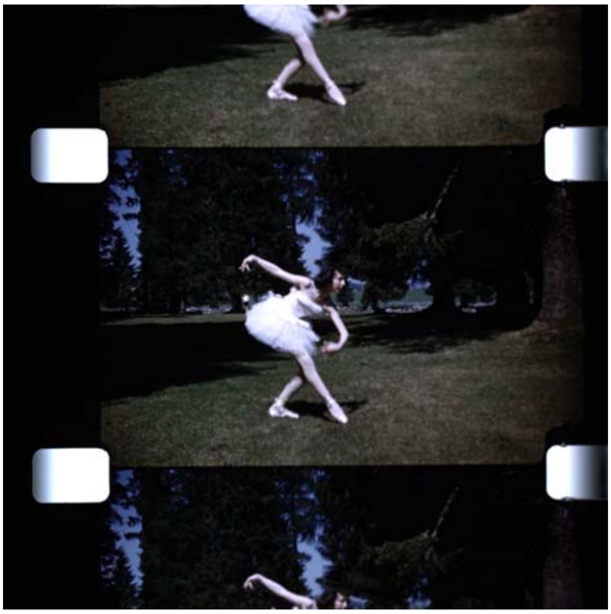


Figure 55 Scans of very dense material such as Kodachrome results in severe clipping both of the blacks and highlights on the D-Archiver Cine10-A

Scanning was a straightforward process done by Reto Kromer, the owner of AV Preservation by reto.ch. Kromer has vast knowledge of the materials used but seemed a bit restricted at times by the limits of the machine. Most results of the scans of our samples were not very convincing in comparison with the "bigger players". The machine was easily brought to its limits by the high contrasts and dense blacks of Kodachrome and Technicolor prints (Figure 55).

It must be taken into consideration that the D-Archiver Cine10-A is a much less costly unit than most other scanners in our test series. Possibly we might have been able to receive better image data by playing out an image file format of higher bit depth than 10 bit DPX from the 16 bit RAW data accumulated in the scan or, as Kromer suggested, by using the OpenEXR format. We asked for DPX because we did not wish to introduce additional variables when comparing results with those from other machines by using this new format which today is mainly used for special effects work and with which our team had no experience.

While the D-Archiver Cine10-A is able to capture the full film width and also non-standard frame lines, the comparison of the preliminary tests executed by the manufacturer at IBC in Amsterdam in 2013 showed the influence of the knowledge and experience of the scanner operator in handling historical material. The results in color rendition made at reto.ch were above average for the blue tinting, Dufaycolor and Technicolor (Figure 56).

Figure 56 Comparison of scans on the D-Archiver Cine10-A captured by Reto Kromer (left) vs. preliminary test taken at IBC Amsterdam by the manufacturer itself (right) shows the influence on the results of the experience of the scanner operator

The ability to capture the full width of the film is a feature requested frequently by archives and the D-Archiver Cine10-A is one of the few machines in the group we tested which can actually do it. However scanning full width with a resolution limit of 2K does reduce the resolution of the image area to an extent which is visible when compared to using 2K for the image alone. This made the results less sharp in comparison. Later D-Archiver models like the Cine 10-C with a 5K sensor make the decision to scan full width an easier one, since enough resolution remains for the actual image area.

Figure 57 Comparison of scans on the Scanity, 2K at Sound and Vision in Hilversum (left) to the D-Archiver Cine10-A captured by Reto Kromer, also 2K (right) shows banding artifacts in the texture of the Technicolor film

On close inspection the scans showed artifacts in the reproduction of the texture, whether in the graininess of chromogenic films, the Dufaycolor réseau or the texture of Technicolor prints (Figure 57). These problems hint at a weakness in the post-processing of the captured data.

The D-Archiver Cine10-A is an interesting, mechanically very versatile machine with many options geared towards the archival market. A scanner emerging from an inspection table is a concept in development on which several companies like KEM and Kinoton have also picked up. More refinement, probably primarily on the electronic side of image capturing and data processing, is necessary to clearly distance the D-Archiver Cine10-A from the level of an inspection table with a recording option.

4 Subjective and Objective Analyses and Evaluation of Results

Two complementary types of evaluations were conducted on the results: objective measurements and subjective judgments.

Objective analysis is based on measurements that can be done on the scans to be evaluated.

Subjective analysis evaluates the scans based on the judgment of a group of subjects. Examples of subjective analysis are the rating study in which subjects assign a score to each scan according to a catalog of criteria, the pair comparison study in which for each pair of scans the subjects decide which is the better scan according to certain criteria, and the verbose evaluation, a written description of the features that a subject can notice in the scans. The subjective evaluation was conducted with a group of 11 experts (see section *Subjective Evaluation and Results* on pp. 60).

4.1 Resolving Power and Sharpness

This section reports the results of the evaluation of the scanners performances in terms of resolving power and sharpness.

Figure 58 ARRI AQUA test leader: specifications frame (top) and test target chosen for this investigation (bottom). The green rectangle highlights the pattern set which was analyzed.

ARRI AQUA test leaders were created with the ARRILASER 86 (parameters reported in Figure 58, top) and imaged with the scanners. The frame having magenta patterns (Figure 58, bottom) was chosen for this test, analyzing the central set of circular concentric patterns (indicated by the green rectangle).

An oblique line ($\approx$ 22°) orthogonally crossing the line patterns with increasing spatial frequencies was drawn in Image J (NIH, USA) (yellow line in Figure 59, left). The profile of the pixel values of the GREEN-channel along the line was plotted and saved (Figure 59, right), averaging a number of parallel lines.

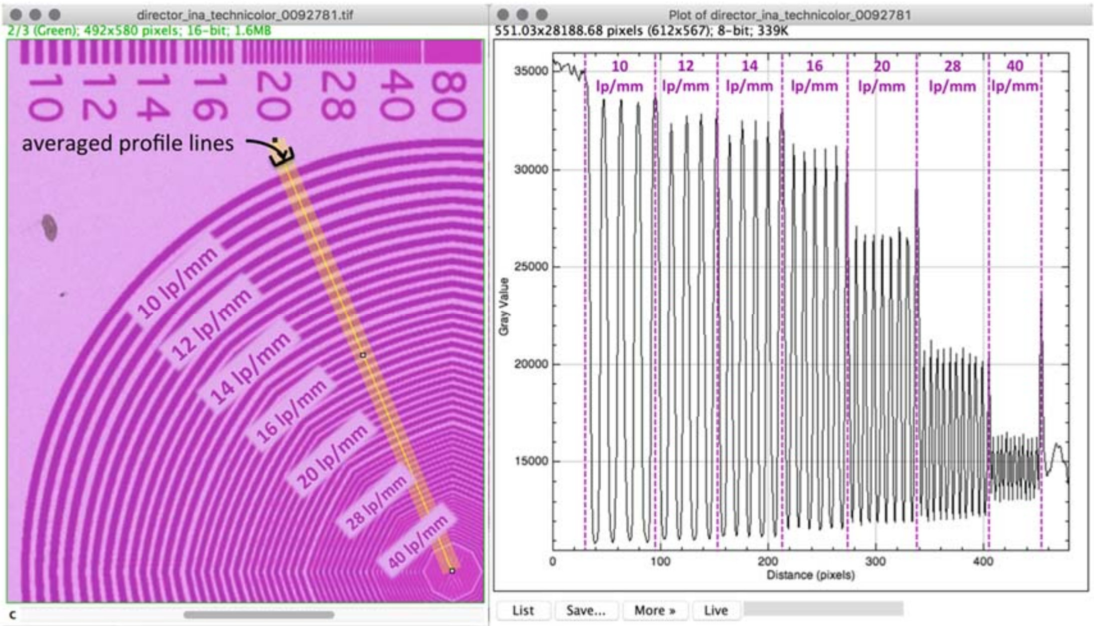


Figure 59 Left: portion of the central set of concentric patterns with the line drawn in yellow and labels indicating the spatial frequencies. Right: corresponding profile of the pixel values.

The concepts that inspired this design for the present method can be found here.[21] The target is considered to have only two precise optical density values: a 'high' corresponding to the dark lines, and a 'low' corresponding to the light space between lines. The attenuation of the contrast between 'highs' and 'lows' (as for instance the one reported in Figure 59) is considered to be due to the blurring of the scanner that reduces the contrast high/low with increasing spatial frequencies. Each scanner is an imaging system consisting of a chain of components (light source, lens, digital image sensor, de-mosaicing and processing software). The overall blurring found in the analyzed digital images is the effect of the limitations of all these components. No investigation will be done here on the limitations of the single components.

For all the spatial frequencies of the concentric patterns (ξ = 10, 12, 14, 16, 20, 28 and 40 lp/mm)[22] two values were calculated:

1) the average value of the local minima corresponding to the dark lines of the pattern ($V_{dark}(\xi)$) and
2) the average value of the local maxima corresponding to the light space between the lines ($V_{light}(\xi)$).

[21] Imatest LLC, "Sharpness: What is it and how is it measured?" - www.imatest.com/docs/sharpness/ (visited 6 Dec. 2016)

[22] A pattern with 80 lp/mm is present in the target, but this spatial frequency is too high to be recorded by the 4K film recorder.

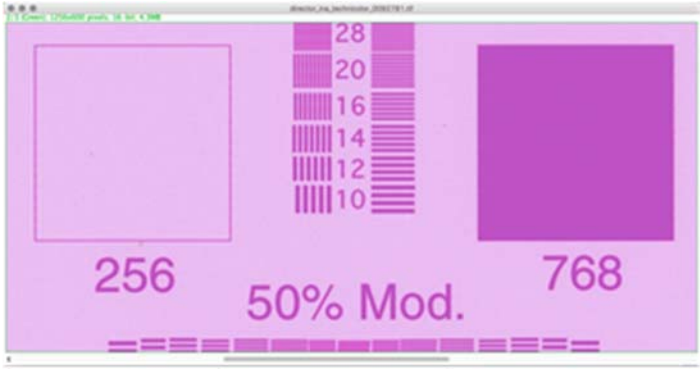


Figure 60 Extended dark and light areas of the selected frame, which were considered as the original values

The average values of the GREEN channel of the extended dark and light areas (see image on right) were considered as the 'original' values without blurring for $\xi = 0$ ($V_{dark}(0)$ and $V_{light}(0)$).

The *resolving power* of a scanner can be described by the fraction of reproduced contrast (**F**) as a function of the spatial frequency of the bar patterns:[23]

$$F(\xi) = \left(V_{light}(\xi) - V_{dark}(\xi)\right) / \left(V_{light}(0) - V_{dark}(0)\right) \tag{8}$$

F could be measured only for the set of specific ξ present in the target. In the plot of Figure 61 line between the measured points was also drawn to increase readability.

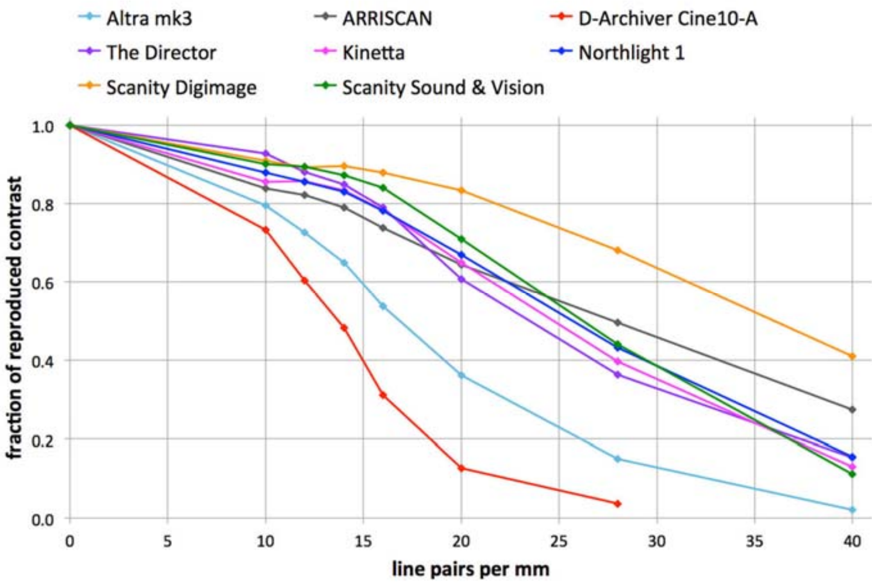


Figure 61 Fraction of reproduced contrast as function of spatial frequency for the analyzed scanners

F is generally a monotonically decreasing function, which is normalized to 1 for $\xi = 0$. The higher the **F** value, the better the ability of the scanner to distinguish detail in the film. The

[23] The contrast is interpreted here as simple difference between the dark and light values

functions plotted in Figure 4 intersect at several points, so a straightforward ranking cannot be done. Some functions are not monotonically decreasing throughout, presumably because of sharpening.[24]

The scanners produce images with different numbers of pixels, and the total number of pixels along the film width covers different portions of the full film width. These diversified conditions result in diversified spatial resolutions, and the terminology "2K, 4K, 6K, etc." are a mere approximation. The table on the following page reports the precise spatial resolutions in 'pixels per millimeter' and the corresponding theoretical limit defined by the sampling theorem (Nyquist limit).

Higher resolving power is achieved with higher spatial resolution, but higher resolution requires larger data storage. For this reason it is interesting to evaluate the *sharpness* of the images, which indicates 'how well the scanner utilizes the pixels'. To this aim, the unit of the spatial frequency must be changed, expressing the function **F** in terms of line pairs per pixels. The unit change is performed with the following formula:

$$\text{spatial frequency [lp/pixel]} = \frac{\text{spatial frequency [lp/mm]}}{\text{spatial resolution [pixel/mm]}} \tag{9}$$

A second plot is obtained (Figure 62) where the spacing of the data changes with the spatial resolution. The higher is the value of **F**, the sharper is the image irrespective of its spatial resolution.

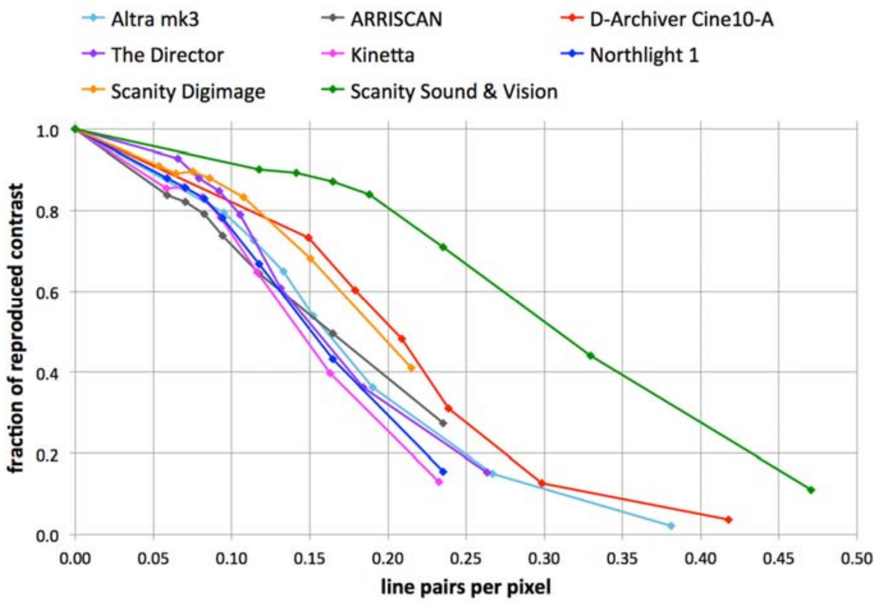
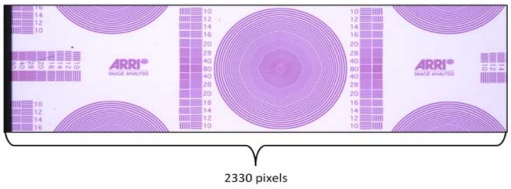
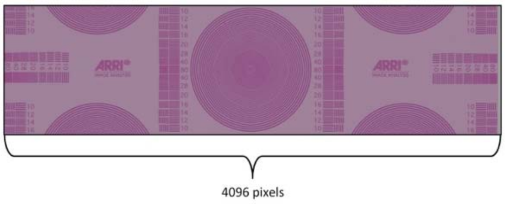
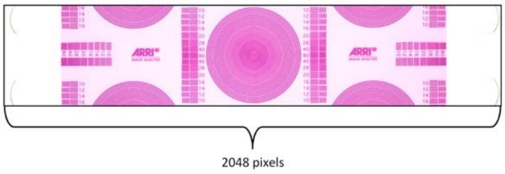
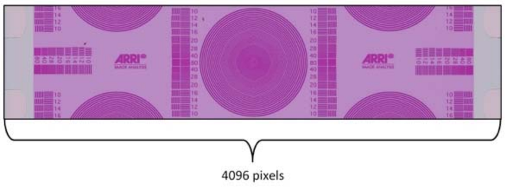
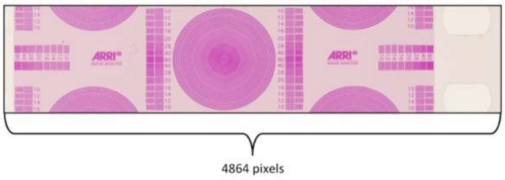
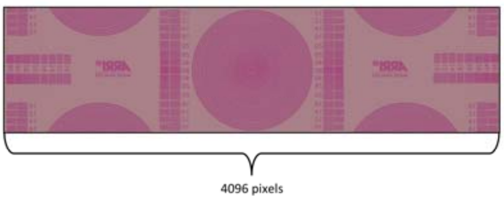
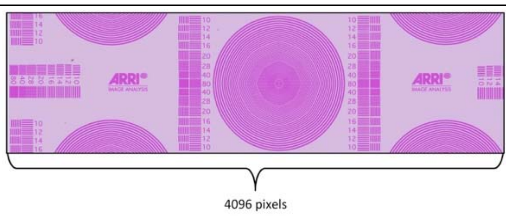
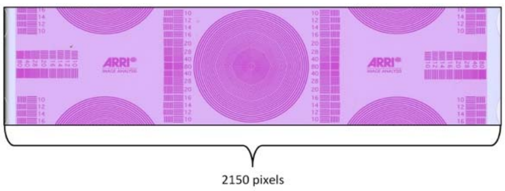


Figure 62 The function F in terms of line pairs per pixel

[24] Imatest LLC, "Introduction to sharpening" - http://www.imatest.com/docs/sharpening/ (visited 6 Dec. 2016).

Table 3 Width of the scans in pixels and the according Spatial Resolution in pixels per millimeter as well as the Nyquist limit in line pairs per millimeter

	Film width included in the digital image and number of pixels utilized	Spatial resolution [pxl/mm]	Nyquist limit [lp/mm]
Altra mk3		105	52.5
ARRISCAN		170	85
D-Archiver Cine10-A		67	33.5
The Director		152	76
Kinetta		172	86
Northlight 1		170	85
Scanity (Digimage)		186	93
Scanity (Sound & Vision)		85	42.5

4.2 Subjective Evaluation and Results

4.2.1 Introduction

To complete our observations and investigation of the scanner–material interaction and the objective analysis of the data, we decided to execute a subjective evaluation of the raw scans with a group of 11 subjects in the color grading suite at Cinegrell Postproduction. All the subjects had a specific background in judging image quality. Three of them were professional color graders and/or scanner operators. Two of them were advanced film scholars, two were imaging scientists, and four were PhD students with special training in historical film colors. For some part of the evaluation two restorers were also present.

For the evaluation, the subjects received an introduction into the concepts to be evaluated:

- Color rendition (*Farbwiedergabe*):[25]
  An important criterion to be evaluated is the color rendition of the scans. This criterion is related to the saturation of the colors, the brightness, the presence of color cast. Only for the 35mm films the color rendition was evaluated in direct comparison to the 35mm print projected on the LocPro (no 16mm option was available on the LocPro).
- Global contrast (*globale Kontrastwiedergabe*):
  Global contrast is related to the rendition of blacks, highlights and mid-tones.
- Local contrast (*lokale Kontrastwiedergabe*):
  Local contrast is associated with the crispness of small-scale details and related to perceived sharpness.
- Contrast range (*Kontrastumfang*):
  Takes the rendition of deep blacks and extreme highlights into account and whether they still contain details or whether any sort of clipping occurs.
- Perceived sharpness (*wahrgenommene Schärfe*):
  For human visual perception sharpness is a complicated amalgam consisting of technical resolution, small-scale contrast, and focus in relation to the viewing distance.
- Texture rendition (*Wiedergabe der Textur*) (Réseau):
  Graininess and texture are important aspects of a film's authentic appearance and refer to the representation of each film stock's typical *faktura*, i.e. the interplay between dye clouds or applied dyes, silver image, or réseau, emulsion and base.
- Perceived resolution (*wahrgenommene Auflösung*):
  While technical resolution was measured by MTF (see the corresponding section above), perceived resolution of the scans was evaluated in comparison to the source material.
- Image steadiness (*Bildstabilität*):
  Stabilization of the frames by scanning.

[25] The subjective evaluation was conducted in German, since the subjects were (Swiss) German native speakers; hence the German term that was used in the evaluation sheets is indicated in brackets.

- Overall impression (*Gesamteindruck*):
  Refers to the subject's overall evaluation regardless of performance on individual items.

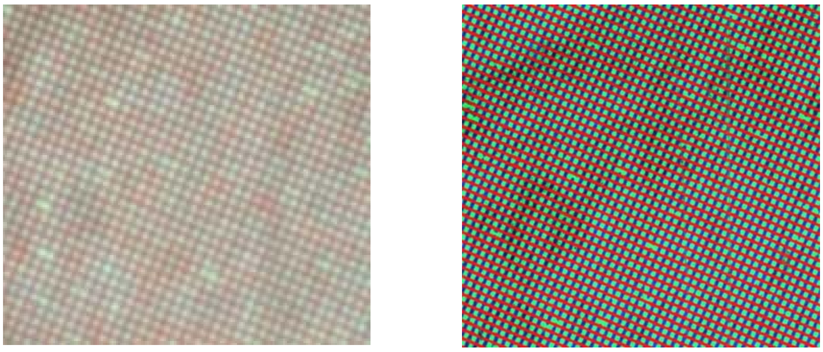


Figure 63 Texture rendition and perceived resolution: Comparison of the Dufaycolor réseau of the Altra mk3 in 2K and ARRISCAN in 4K

As mentioned the 35mm film materials were evaluated based on a comparison with the screened film from the ARRI LocPro 35, while no such possibility was available for the 16mm films. However, it turned out in the analyses of the complete sets of data, that the most significant results stemmed from the 35mm films, which covered three of the most important factors for the evaluation of scanning. Each of the three 35mm film stocks represents specific requirements, while the outcomes of the 16mm tests are generally less significant.

- **The blue tinted film** is representative of early applied colors that combine dyes with a black-and-white silver image on nitrate stock. Similar results were obtained with other tinted stocks in the DIASTOR case studies Digital Desmet (see Flueckiger et al. 2016) and DER MÄRCHENWALD (see report on DIASTOR's results page https://diastor.ch/2016/05/31/results/).
- **Dufaycolor** represents a highly informative stock for the evaluation of scanner performance, as was also apparent in the objective analyses. The diagonal réseau with its three primary colors distributed in a regular pattern proved extremely valuable for the investigation of the complete chain, from the sensor–illumination interaction to the (hidden) image post-processing. Artifacts, insufficient color separation, contrast rendition, and optical resolution all become instantly available for subjective and objective analyses.
- **Technicolor** represents very dense positive stocks with steep gradation and therefore with high contrasts. Especially the blacks posed almost unsurmountable problems for many scanners that are in line with similar results from the scans of color reversal films such as Ektachrome and Kodachrome.

Despite the fact that the subjective evaluation delivered highly significant results, these results must be considered with care. There are several critical issues with regard to subjective evaluation of raw scans. First of all, as mentioned in the *Introduction* on pp. 7, the scans could not be produced in a highly standardized way for the reasons discussed. Secondly, and not less importantly, raw scans are not meant to be the final result to be shown to a public. They must be evaluated based on their potential for a successful color grading that is hard to assess except for highly trained staff, and such persons were present in the subjective evaluation.

As also elaborated in the *Introduction*, we counteract these weaknesses by considering all the relevant factors and by contextualizing the results. It must be said, for instance, that the optical resolution and focus were difficult to evaluate based on the relatively small screen and a projection limited to 2K. Perceived sharpness— as mentioned above—must be distinguished from technical resolution and optical focus.

4.2.2 Statistical Analysis of the Results[26]

For test of significance, all data was z-transformed for each person (mean of 0, standard-deviation of 1). This was necessary due to wide difference in answers and thus the total mean value of all answers between the persons (mean values of all answers went from 3.2 to 4.63). The data was z-transformed over all questions, scanners and materials for each person. Thus a value of 0 would be the mean scanner-material pair. 50% of the other scanners and/or materials are judged better, 50% worse. The values for the overall ANOVA and detailed t-tests was a mean from every question including the ‘overall opinion’ (not the overall opinion alone).

For an overall ANOVA the film materials considered were Dufaycolor, Kodachrome, Technicolor and the tinted sample and for the scanners ARRISCAN, D-Archiver Cine10-A, The Director, Scanity-Sound & Vision and Kinetta. Some materials and scanners had to be excluded so that the ANOVA could be calculated properly.

There were two factors 'material' (four elements) and 'scanner' (five elements) with an interaction material x scanner. The factor scanner was significant ($p = 0.05$). Some scanners were judged better than others over all materials. The factor 'material' was not significant, meaning that the different materials did not differ from each other in their total judgments over all scanners. Nevertheless, the interaction material x scanner was significant ($p < 0.001$). This means that even if the material was judged the same, not every scanner was as good for each material. Material and scanners were chosen that every included material could be tested for every included scanner and vice versa.

The difference between scanners in each material was tested with t-tests in JASP. The tests were made for each material except for the faded print and black and white, which had just one scanner tested.

[26] The statistical analysis of the results was executed by Stefan Amstutz, Department of Media Psychology, University of Bern, under the guidance of Miriam Loertscher and Dr. David Weibel.

4.2.2.1 Dufaycolor (35mm)

Arithmetic mean: 3.92

Scanners:

1. The Director (4.48)
2. ARRISCAN (4.28)
3. D-Archiver Cine10-A (3.97)
4. Altra mk3 (3.91)
5. Scanity Digimage (3.73)
6. Scanity Sound & Vision (3.63)
7. Kinetta (3.33)

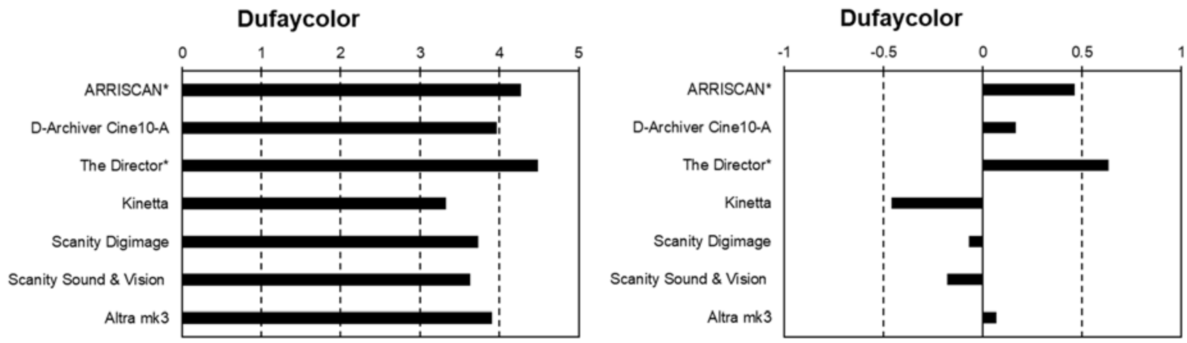


Figure 64 Absolute (left) and relative (right) overall rating for Dufaycolor (* sig. with $p < 0.05$ from other scanners)

Table 4 p-values (significant comparisons above the 5% level are marked in bold)

	The Director	ARRISCAN	D-Archiver Cine10-A	Altra mk3	Scanity Digimage	Scanity S&V
ARRISCAN	.200					
D-Archiver Cine10-A	**.028**	**.045**				
Altra mk3	**.015**	**.010**	.235			
Scanity Digimage	**.003**	**.025**	.125	.236		
Scanity S&V	**<.001**	**.004**	**.049**	.097	.226	
Kinetta	**<.001**	**<.001**	**<.001**	**.001**	**.004**	**.036**

Interpretation: There is no significant difference between The Director und ARRISCAN, but both of them differ significantly from all the other scanners.

4.2.2.2 Technicolor (35mm)

Arithmetic mean: 3.83

Scanners:

1. Kinetta (4.58)
2. Scanity Sound & Vision (4.47)
3. Scanity Digimage (4.26)
4. Northlight 1 (4.25)
5. The Director (4.16)
6. Altra mk3 (4.05)
7. D-Archiver Cine10-A (3.90)
8. ARRISCAN (3.30)

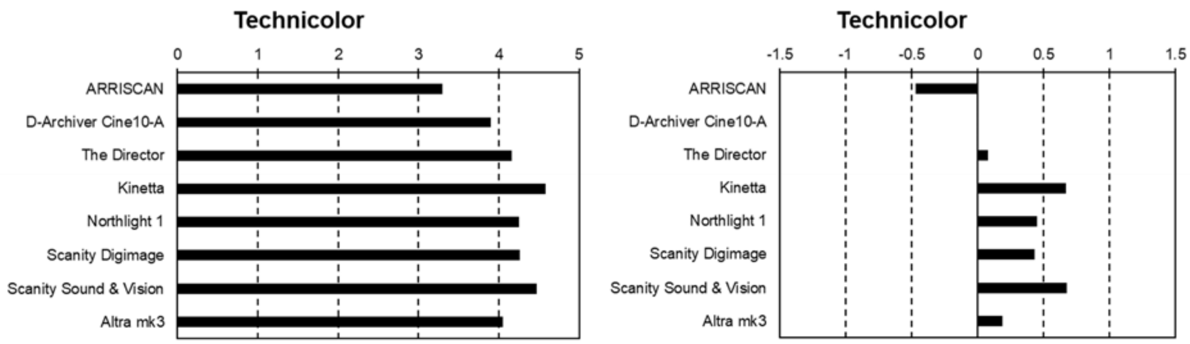


Figure 65 Absolute (left) and relative (right) overall rating for Technicolor

Table 5 p-values (significant comparisons above the 5% level are marked in bold)

	Kinetta	Scanity S&V	Scanity Digimage	Northlight 1	The Director	Altra mk3	D-Archiver Cine 10-A
Scanity S&V	.511						
Scanity Digimage	.133	.055					
Northlight 1	.084	.167	.363				
The Director	**.001**	**.003**	**.012**	.051			
Altra 2K mk3	**.026**	**.020**	.107	.393	.700		
D-Archiver Cine10-A	**.004**	**<.001**	**.021**	**.032**	.345	.199	
ARRISCAN	**<.001**	**<.001**	**<.001**	**.001**	**.003**	**.002**	**.023**

Interpretation: There is no significant difference between the first four scanners Kinetta, Scanity Sound & Vision and Scanity Digimage as well as Northlight 1 while these four scanners differ significantly from the other five scanners (with the exception of Scanity Digimage and Altra mk3).

4.2.2.3 Blue Tinting (35mm)

Arithmetic mean: 3.74

Scanners:

1. Kinetta (4.6)
2. Scanity Sound & Vision (4.27)
3. ARRISCAN (3.94)
4. The Director (3.79)
5. D-Archiver Cine10-A (3.75)
6. Northlight 1 (3.42)
7. Scanity Digimage 4K (3.27)

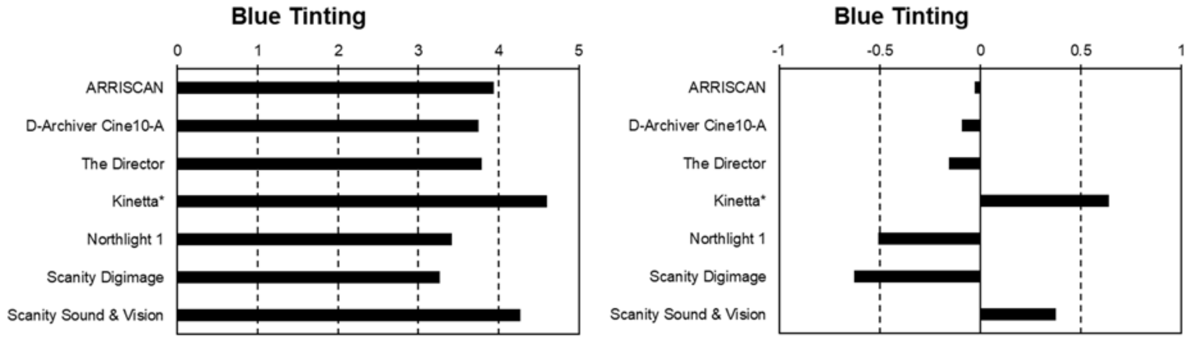


Figure 66 Absolute (left) and relative (right) overall rating for Blue Tinting (* significance $p < 0.05$ from other scanners, except Scanity Sound & Vision)

Table 6 p-values (significant comparisons above the 5% level are marked in bold)

	Kinetta	Scanity S&V	ARRISCAN	The Director	D-Archiver	Northlight 1
Scanity S&V	.085					
ARRISCAN	**.017**	.122				
The Director	**<.001**	**.003**	.302			
D-Archiver Cine10-A	**.001**	**.020**	.365	.668		
Northlight 1	**<.001**	**<.001**	.063	**.023**	**.047**	
Scanity Digimage	**<.001**	**<.001**	**.027**	**.009**	**.004**	.317

Interpretation: There is no significant difference between Kinetta and Scanity Sound & Vision, but both of them differ significantly from all the other scanners.

4.2.2.4 Kodachrome (16mm)

Arithmetic mean: 3.72

Scanners:

1. Scanity Sound & Vision (4.19)
2. The Director (3.99)
3. ARRISCAN (3.93)
4. Kinetta (3.82)
5. Altra mk3 (3.8)
6. Northlight 1 (3.21)
7. D-Archiver Cine10-A (2.95)

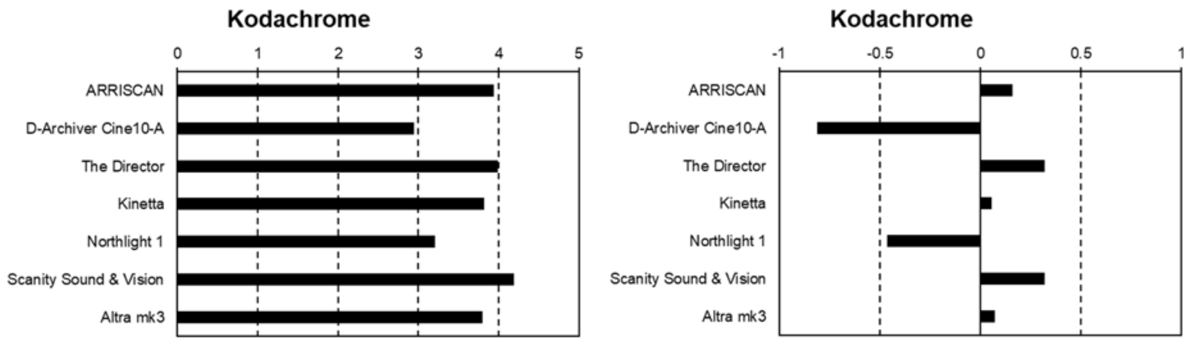


Figure 67 Absolute (left) and relative (right) overall rating for Kodachrome

Table 7 p-values (significant comparisons above the 5% level are marked in bold)

	Scanity S&V	The Director	ARRISCAN	Kinetta	Altra mk3	Northlight 1
The Director	.492					
ARRISCAN	.112	.196				
Kinetta	**.024**	.075	.260			
Altra mk3	**.025**	.063	.258	.586		
Northlight 1	**< .001**	**< .001**	**< .001**	**.002**	**< .001**	
D-Archiver Cine10-A	**< .001**	**< .001**	**< .001**	**< .001**	**< .001**	**.016**

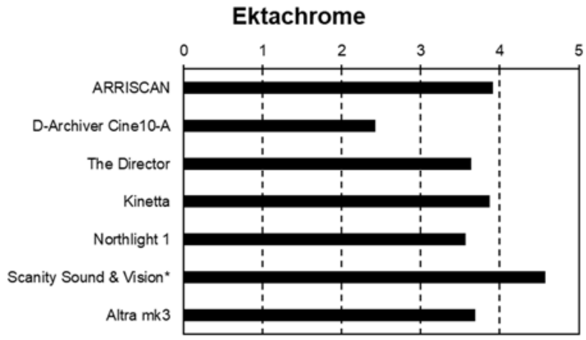
Interpretation: There is no significant difference between the first six scanners. Only Kinetta (rank 4) and Altra mk3 (rank 5) differ significantly from Scanity Sound & Vision (rank 1). Northlight 1 and D-Archiver Cine10-A are rated significantly below all other scanners.

4.2.2.5 Ektachrome (35mm)

Arithmetic mean: 3.67

Scanners:

1. Scanity Sound & Vision (4.57)
2. ARRISCAN (3.92)
3. Kinetta (3.88)
4. Altra mk3 (3.69)
5. The Director (3.64)
6. Northlight 1 (3.57)
7. D-Archiver Cine10-A(2.42)



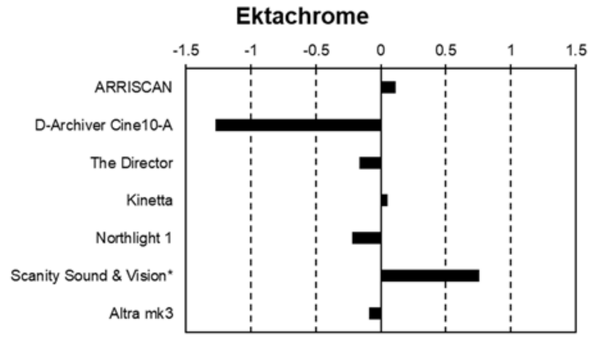


Figure 68 Absolute (left) and relative (right) overall rating for Ektachrome (* sig. with p < 0.05 from other scanners)

Table 8 p-values (significant comparisons above the 5% level are marked in bold)

	Scanity S&V	ARRISCAN	Kinetta	Altra mk3	The Director	Nortlight 1
ARRISCAN	**.002**					
Kinetta	**<.001**	.406				
Altra mk3	**<.001**	**.044**	.218			
The Director	**<.001**	**.012**	.165	.227		
Northlight 1	**<.001**	.051	**.016**	.136	.359	
D-Archiver Cine10-A	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**

Interpretation: Scanity 2k at Sound & Vision is rated significantly better than the other scanners

4.2.2.6 CRI (16mm)

Arithmetic mean: 3.50

Scanners:

1. The Director (3.98)
2. Scanity Sound & Vision (3.92)
3. ARRISCAN (3.9)
4. Altra mk3 (3.63)
5. Northlight 1 (3.42)
6. Kinetta (3.26)
7. D-Archiver Cine10-A (2.32)

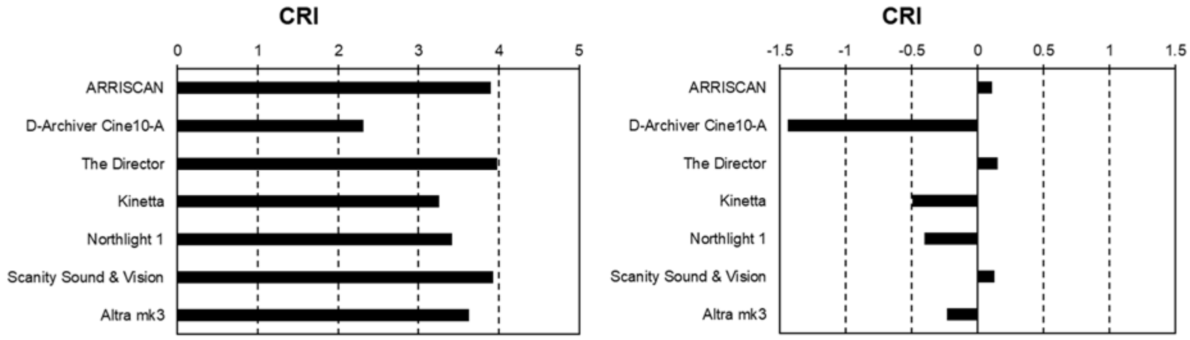


Figure 69 Absolute (left) and relative (right) overall rating for CRI

Table 9 p-values (significant comparisons above the 5% level are marked in bold)

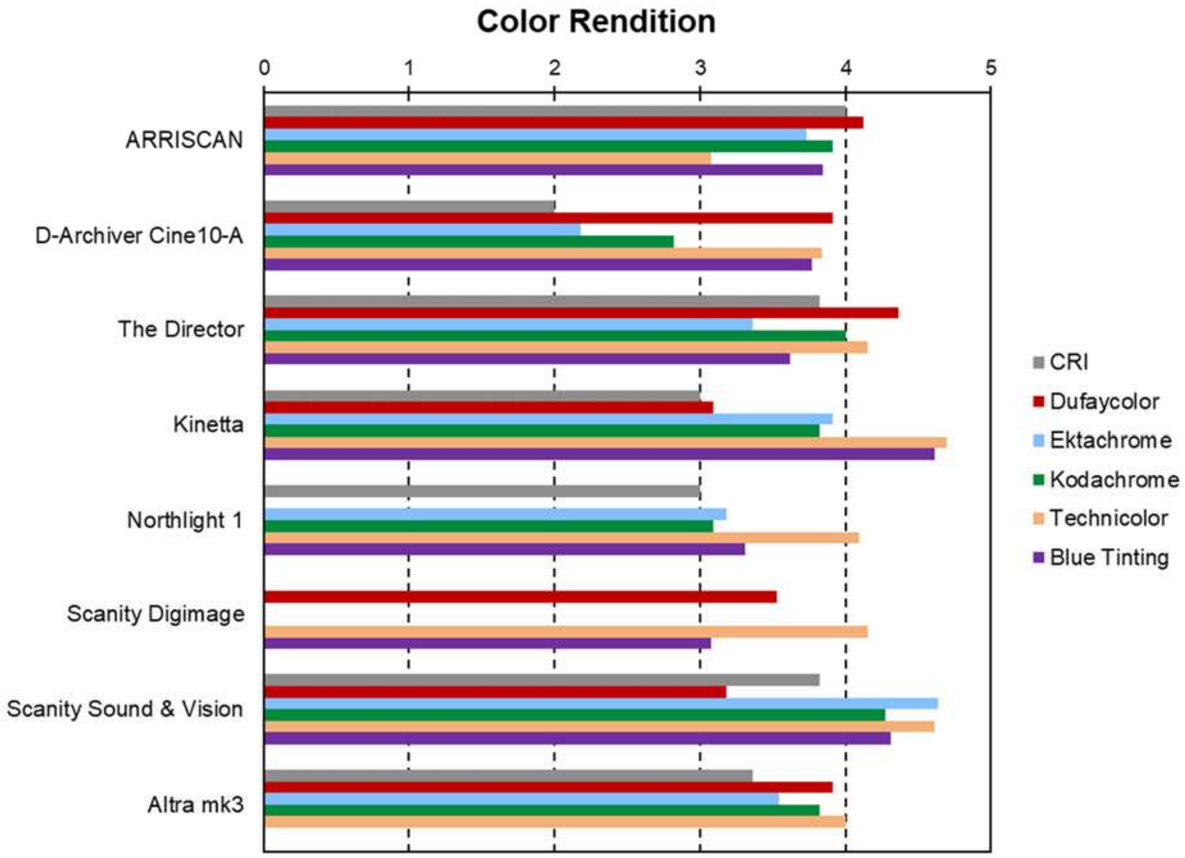
	The Director	Scanity S&V	ARRISCAN	Altra mk3	Northlight 1	Kinetta
Scanity S&V	.396					
ARRISCAN	.364	.421				
Altra mk3	**.009**	**.011**	**.016**			
Northlight 1	**.002**	**.003**	**.005**	.125		
Kinetta	**.016**	**.009**	**.027**	.153	.356	
D-Archiver Cine10-A	**< .001**	**< .001**	**< .001**	**< .001**	**.001**	**.005**

Interpretation: There is no significant difference between The Director, Scanity Sound & Vision and ARRISCAN, but the three scanners differ significantly from all other scanners.

4.2.3 Individual Evaluations

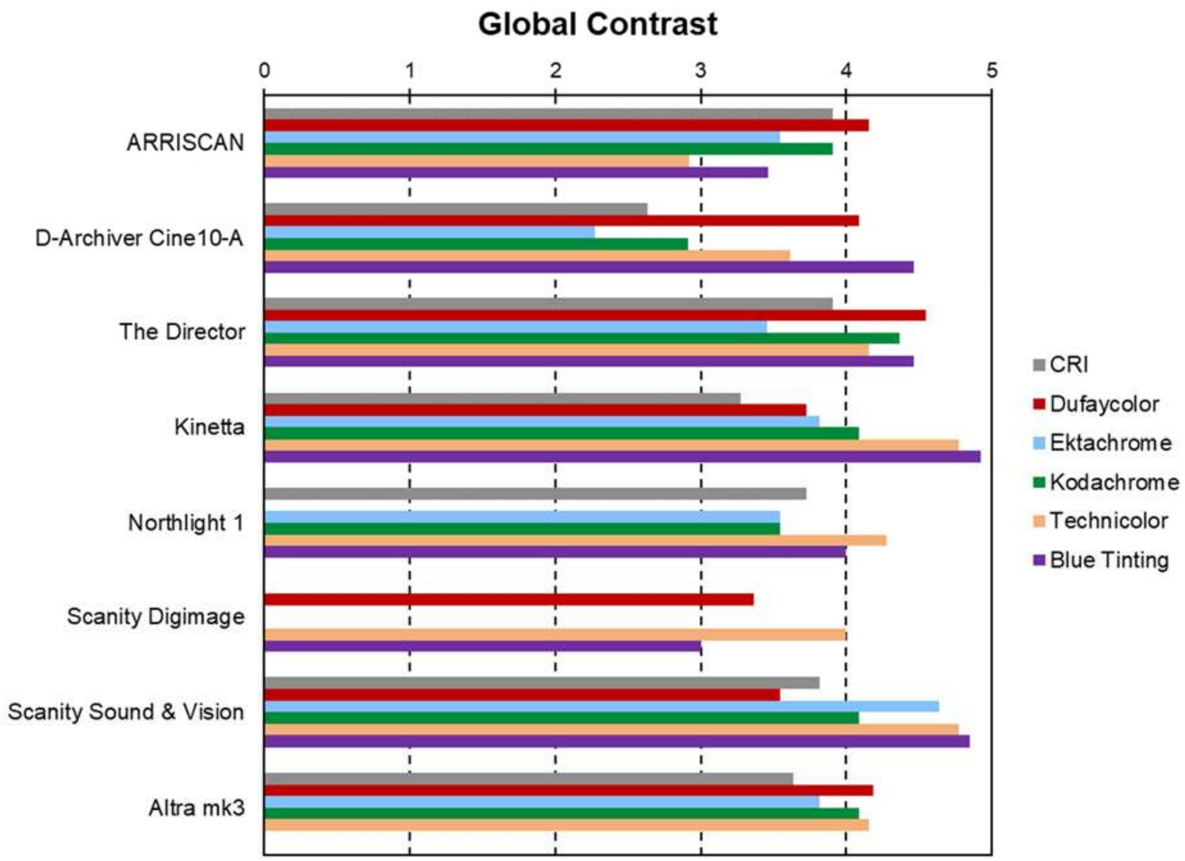
4.2.3.1 Subjective Evaluation Color Rendition (*Farbwiedergabe*)

Color Rendition	ARRISCAN	D-Archiver Cine10-A	The Director	Kinetta	Northlight 1	Scanity Digimage	Scanity Sound & Vision	Altra mk3
CRI	4.00	2.00	3.82	3.00	3.00	0.00	3.82	3.36
Dufaycolor	4.12	3.91	4.36	3.09	0.00	3.52	3.18	3.91
Ektachrome	3.73	2.18	3.36	3.91	3.18	0.00	4.64	3.55
Kodachrome	3.91	2.82	4.00	3.82	3.09	0.00	4.27	3.82
Technicolor	3.08	3.83	4.15	4.69	4.09	4.15	4.62	4.00
Blue Tinting	3.85	3.77	3.62	4.62	3.31	3.08	4.31	0.00



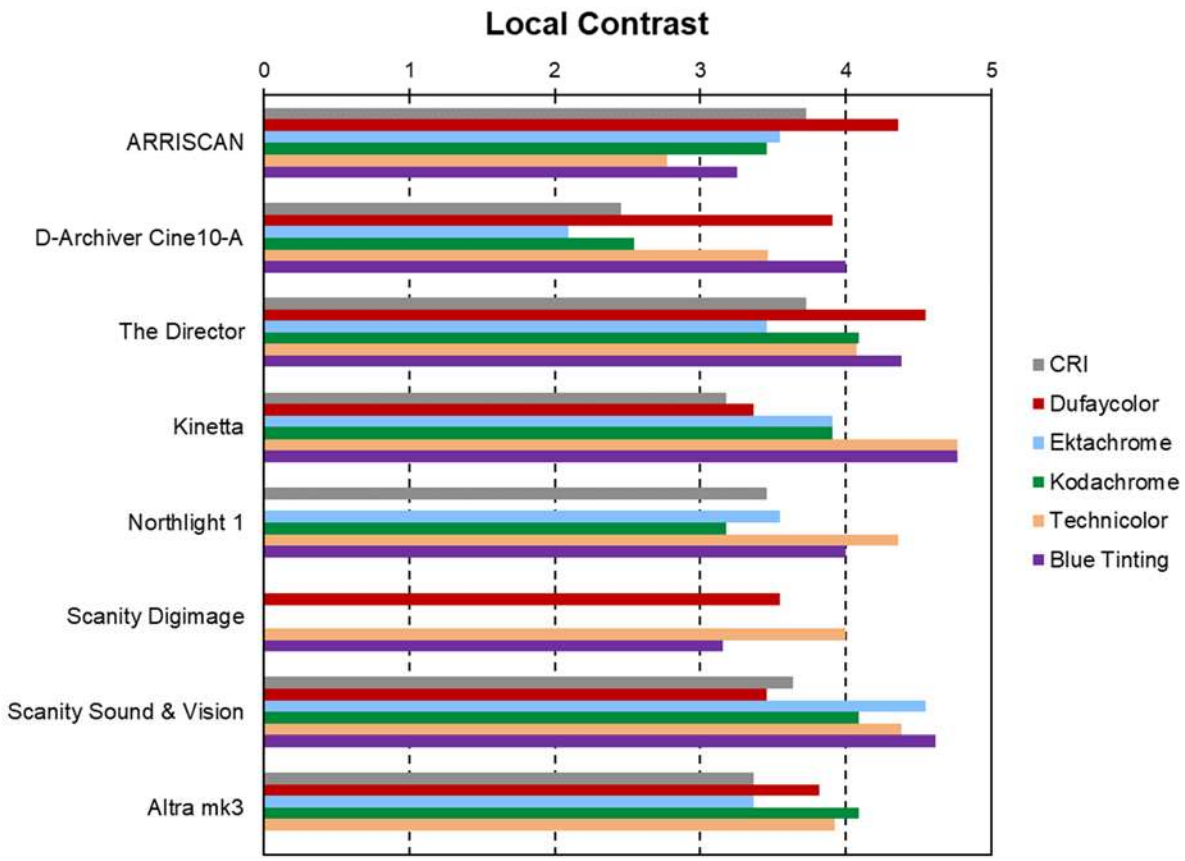
4.2.3.2 Subjective Evaluation Global Contrast (*globale Kontrastwiedergabe*)

Global Contrast	ARRISCAN	D-Archiver Cine10-A	The Director	Kinetta	Northlight 1	Scanity Digimage	Scanity Sound & Vision	Altra mk3
CRI	3.91	2.64	3.91	3.27	3.73	0.00	3.82	3.64
Dufaycolor	4.15	4.09	4.55	3.73	0.00	3.36	3.55	4.18
Ektachrome	3.55	2.27	3.45	3.82	3.55	0.00	4.64	3.82
Kodachrome	3.91	2.91	4.36	4.09	3.55	0.00	4.09	4.09
Technicolor	2.92	3.62	4.15	4.77	4.27	4.00	4.77	4.15
Blue Tinting	3.46	4.46	4.46	4.92	4.00	3.00	4.85	0.00



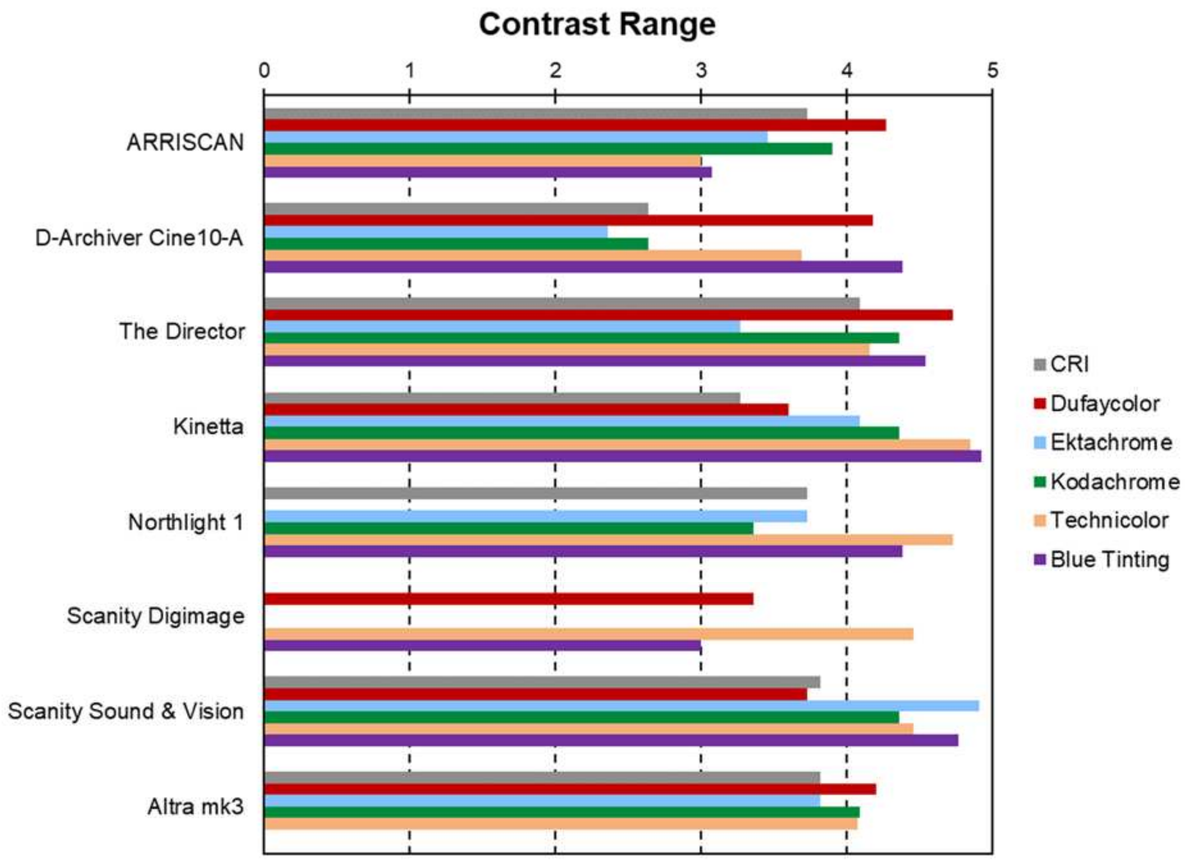
4.2.3.3 Subjective Evaluation Local Contrast (*lokale Kontrastwiedergabe*)

Local Contrast	ARRISCAN	D-Archiver Cine10-A	The Director	Kinetta	Northlight 1	Scanity Digimage	Scanity Sound & Vision	Altra mk3
CRI	3.73	2.45	3.73	3.18	3.45	0.00	3.64	3.36
Dufaycolor	4.36	3.91	4.55	3.36	0.00	3.55	3.45	3.82
Ektachrome	3.55	2.09	3.45	3.91	3.55	0.00	4.55	3.36
Kodachrome	3.45	2.55	4.09	3.91	3.18	0.00	4.09	4.09
Technicolor	2.77	3.46	4.08	4.77	4.36	4.00	4.38	3.92
Blue Tinting	3.25	4.00	4.38	4.77	4.00	3.15	4.62	0.00



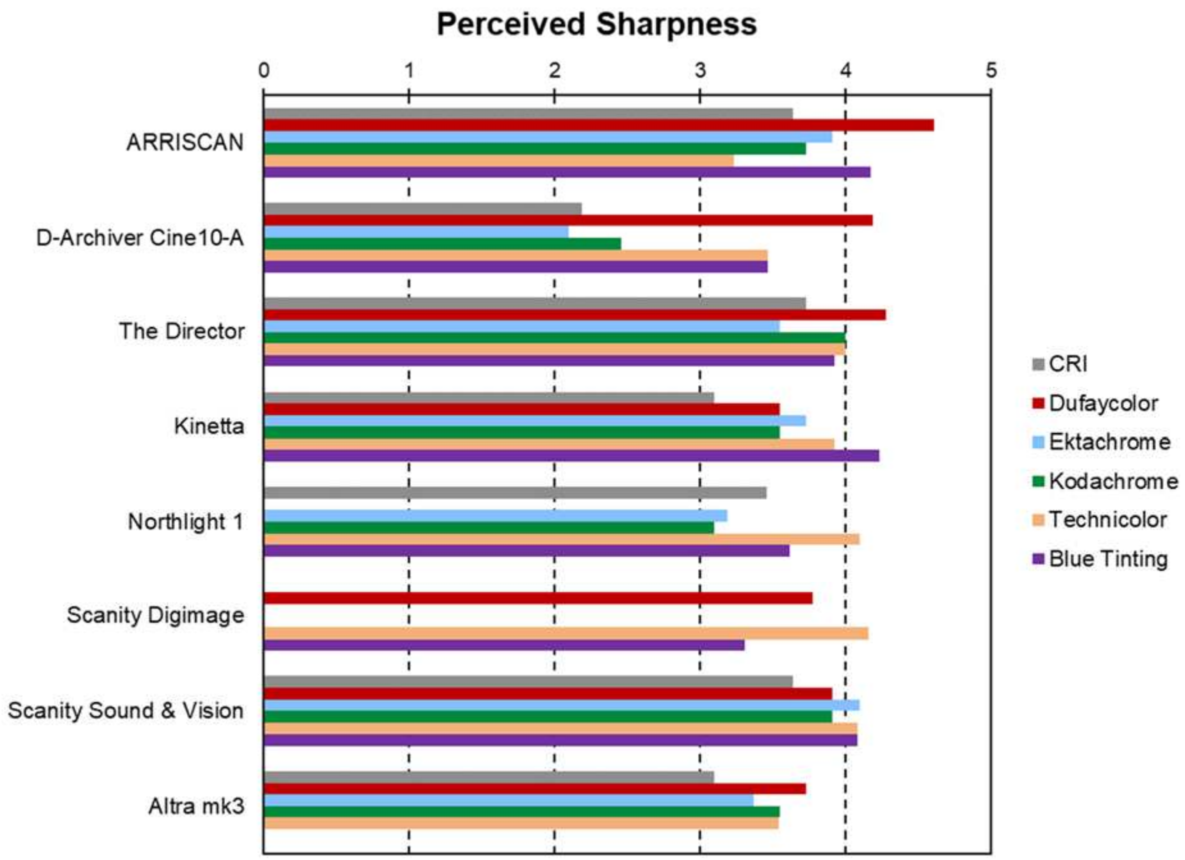
4.2.3.4 Subjective Evaluation Contrast Range (*Kontrastumfang*)

Contrast Range	ARRISCAN	D-Archiver Cine10-A	The Director	Kinetta	Northlight 1	Scanity Digimage	Scanity Sound & Vision	Altra mk3
CRI	3.73	2.64	4.09	3.27	3.73	0.00	3.82	3.82
Dufaycolor	4.27	4.18	4.73	3.60	0.00	3.36	3.73	4.20
Ektachrome	3.45	2.36	3.27	4.09	3.73	0.00	4.91	3.82
Kodachrome	3.90	2.64	4.36	4.36	3.36	0.00	4.36	4.09
Technicolor	3.00	3.69	4.15	4.85	4.73	4.46	4.46	4.08
Blue Tinting	3.08	4.38	4.54	4.92	4.38	3.00	4.77	0.00



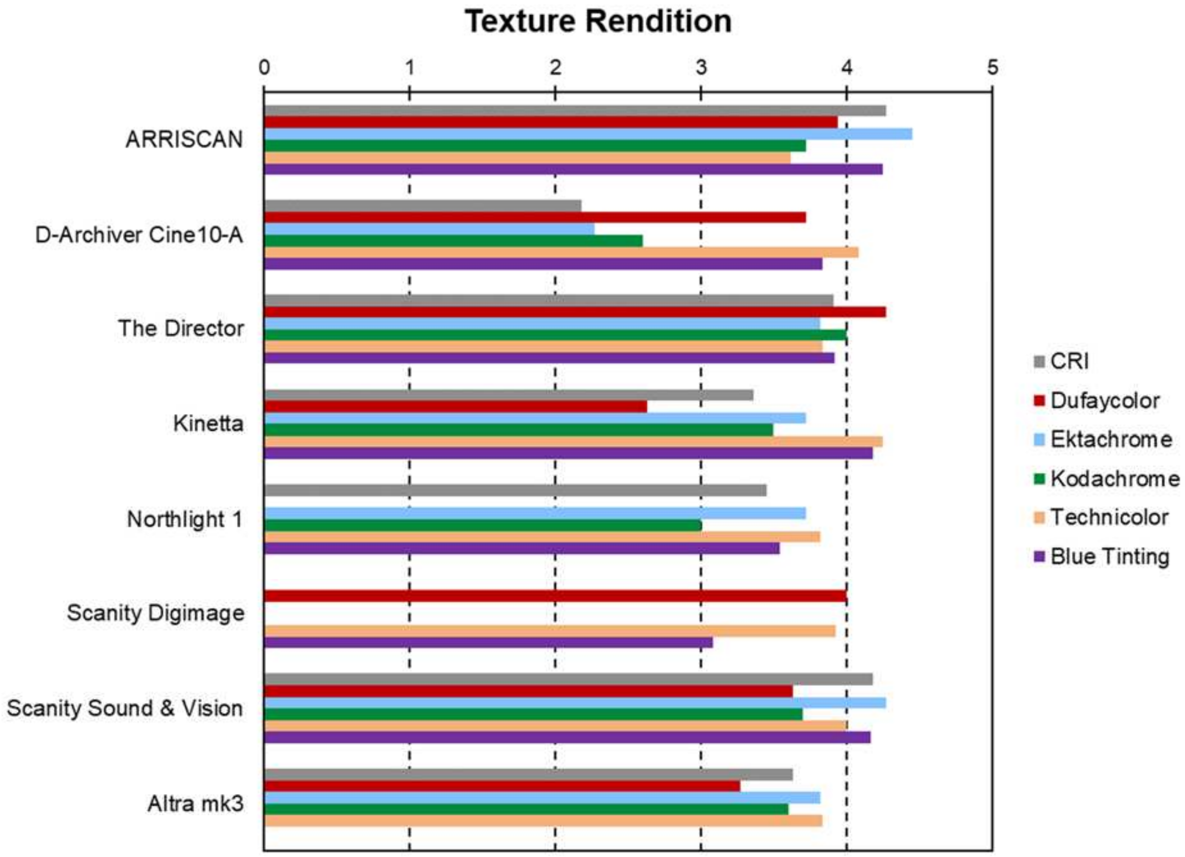
4.2.3.5 Subjective Evaluation Perceived Sharpness (*wahrgenommene Schärfe*)

Perceived Sharpness	ARRISCAN	D-Archiver Cine10-A	The Director	Kinetta	Northlight 1	Scanity Digimage	Scanity Sound & Vision	Altra mk3
CRI	3.64	2.18	3.73	3.09	3.45	0.00	3.64	3.09
Dufaycolor	4.61	4.18	4.27	3.55	0.00	3.77	3.91	3.73
Ektachrome	3.91	2.09	3.55	3.73	3.18	0.00	4.09	3.36
Kodachrome	3.73	2.45	4.00	3.55	3.09	0.00	3.91	3.55
Technicolor	3.23	3.46	4.00	3.92	4.09	4.15	4.08	3.54
Blue Tinting	4.17	3.46	3.92	4.23	3.62	3.31	4.08	0.00



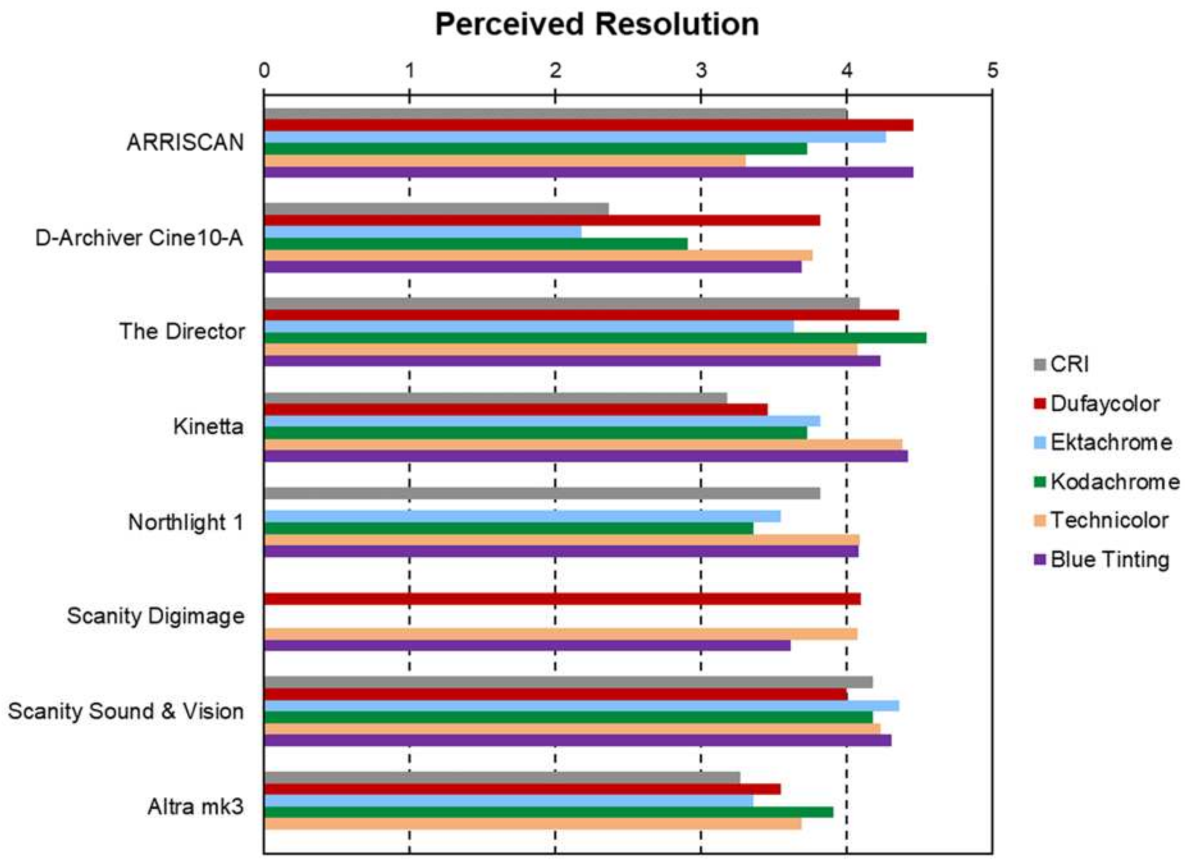
4.2.3.6 Subjective Evaluation Texture Rendition (*Wiedergabe der Textur, Réseau*)

Texture Rendition	ARRISCAN	D-Archiver Cine10-A	The Director	Kinetta	Northlight 1	Scanity Digimage	Scanity Sound & Vision	Altra mk3
CRI	4.27	2.18	3.91	3.36	3.45	0.00	4.18	3.64
Dufaycolor	3.94	3.73	4.27	2.64	0.00	4.00	3.64	3.27
Ektachrome	4.45	2.27	3.82	3.73	3.73	0.00	4.27	3.82
Kodachrome	3.73	2.60	4.00	3.50	3.00	0.00	3.70	3.60
Technicolor	3.62	4.08	3.83	4.25	3.82	3.92	4.00	3.83
Blue Tinting	4.25	3.83	3.92	4.18	3.55	3.08	4.17	0.00



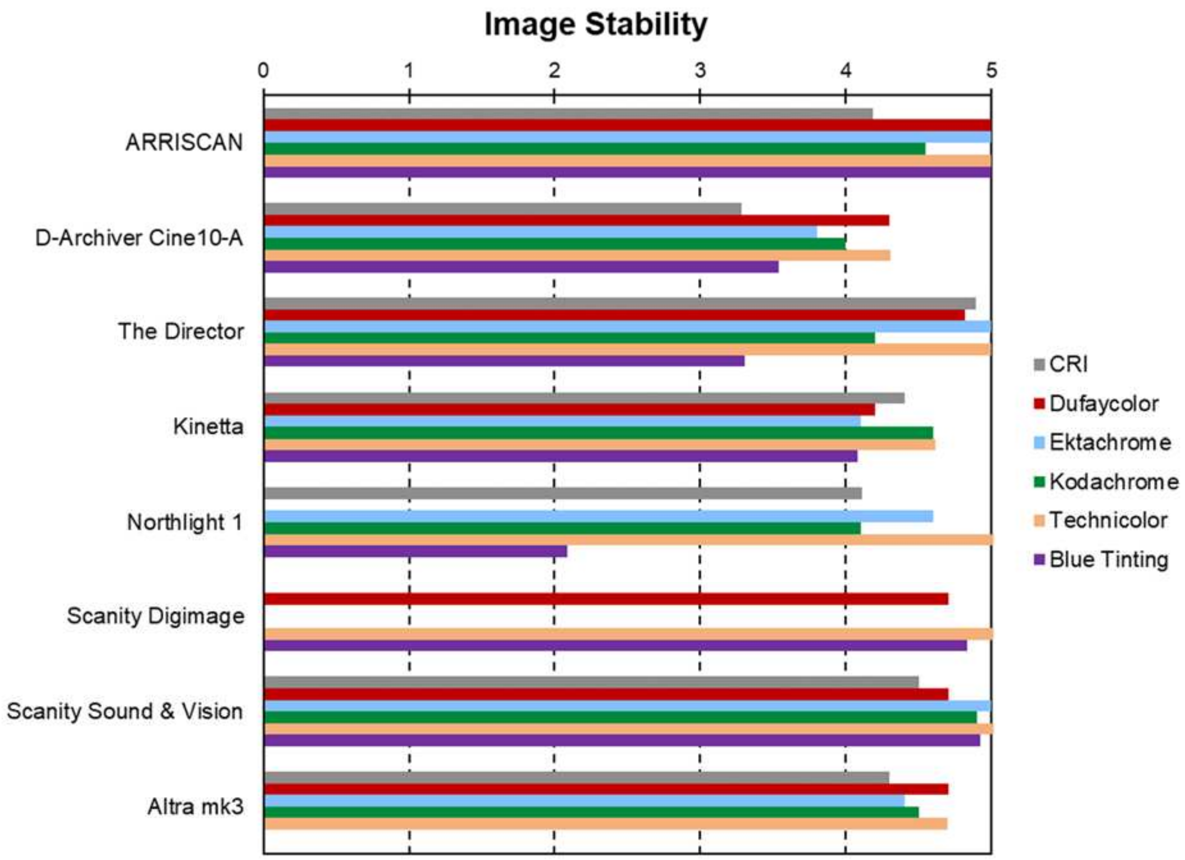
4.2.3.7 Subjective Evaluation Perceived Resolution (*wahrgenommene Auflösung*)

Perceived Resolution	ARRISCAN	D-Archiver Cine10-A	The Director	Kinetta	Northlight 1	Scanity Digimage	Scanity Sound & Vision	Altra mk3
CRI	4.00	2.36	4.09	3.18	3.82	0.00	4.18	3.27
Dufaycolor	4.45	3.82	4.36	3.45	0.00	4.10	4.00	3.55
Ektachrome	4.27	2.18	3.64	3.82	3.55	0.00	4.36	3.36
Kodachrome	3.73	2.91	4.55	3.73	3.36	0.00	4.18	3.91
Technicolor	3.31	3.77	4.08	4.38	4.09	4.08	4.23	3.69
Blue Tinting	4.45	3.69	4.23	4.42	4.08	3.62	4.31	0.00



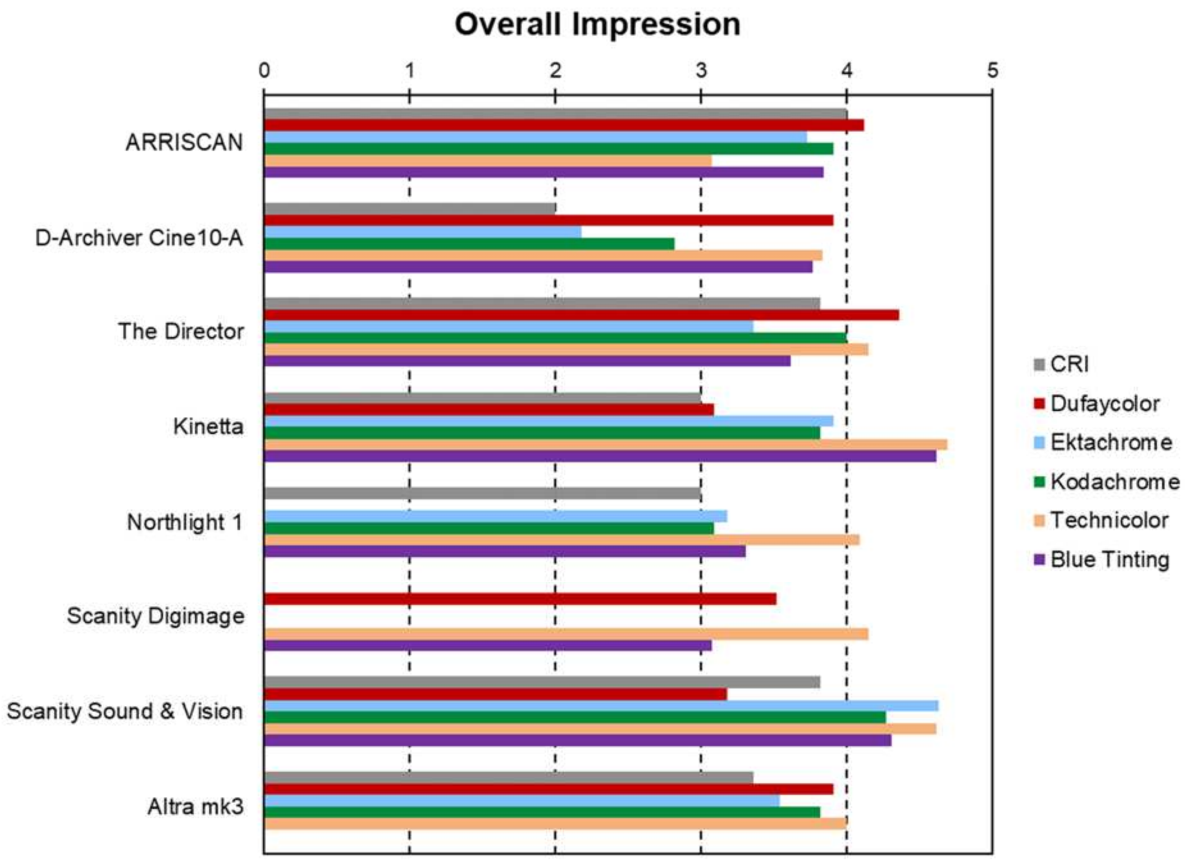
4.2.3.8 Subjective Evaluation Image Stability (*Bildstabilität*)

Image Stability	ARRISCAN	D-Archiver Cine10-A	The Director	Kinetta	Northlight 1	Scanity Digimage	Scanity Sound & Vision	Altra mk3
CRI	4.18	3.29	4.89	4.40	4.11	0.00	4.50	4.30
Dufaycolor	5.00	4.30	4.82	4.20	0.00	4.70	4.70	4.70
Ektachrome	5.00	3.80	5.00	4.10	4.60	0.00	5.00	4.40
Kodachrome	4.55	4.00	4.20	4.60	4.10	0.00	4.90	4.50
Technicolor	5.00	4.31	5.00	4.62	5.27	5.08	5.31	4.69
Blue Tinting	5.00	3.54	3.31	4.08	2.08	4.83	4.92	0.00



4.2.3.9 Subjective Evaluation Overall Impression (*Gesamteindruck*)

Overall Impression	ARRISCAN	D-Archiver Cine10-A	The Director	Kinetta	Northlight 1	Scanity Digimage	Scanity Sound & Vision	Altra mk3
CRI	4.00	2.00	3.82	3.00	3.00	0.00	3.82	3.36
Dufaycolor	4.12	3.91	4.36	3.09	0.00	3.52	3.18	3.91
Ektachrome	3.73	2.18	3.36	3.91	3.18	0.00	4.64	3.55
Kodachrome	3.91	2.82	4.00	3.82	3.09	0.00	4.27	3.82
Technicolor	3.08	3.83	4.15	4.69	4.09	4.15	4.62	4.00
Blue Tinting	3.85	3.77	3.62	4.62	3.31	3.08	4.31	0.00



4.2.4 Result Summary

The scanners' technical specifications and the results of chapters 4.1 and 4.2 are shown as an overview presentation below.

Figure 70 shows the technical specifications in a spider chart. The quality of each technical property is indicated on a linear axis and the axes for the various properties are combined as a star shape. Connecting the points on all axes yields an irregular polygon whose shape and size indicate the level of performance of the machine. Each axis has a separate scale with the minimum value at the inner black ring and the maximum at the outer black ring. Only the axes' scales of "Max. resolution" and "Max. bitdepth" are based on numerical values which are 0K to 6K resolution and 0 bits to 16 bits per color channel, respectively. All other scales are based on available options or flexibility of the scanner toward a particular feature.

Figure 71 summarizes the results of the subjective analysis. The axis "Sharpness at 0.2 line pairs/pixel" relates to the measurements in chapter 4.1 and represents values between zero and 1. All other axes have scales from 2 to 5 and indicate the results of the subjective analysis in chapters 4.2.3.1 to 4.2.3.9. Each value reflects one aspect of the images obtained from the indicated scanner, averaged across all film samples.

Figure 72 represents the results of the overall impression of the subjective analysis (chapter 4.2.3.9) dissecting the results of the individual film samples per scanner. All axes have scales of 2 to 5 from inner to outer black ring.

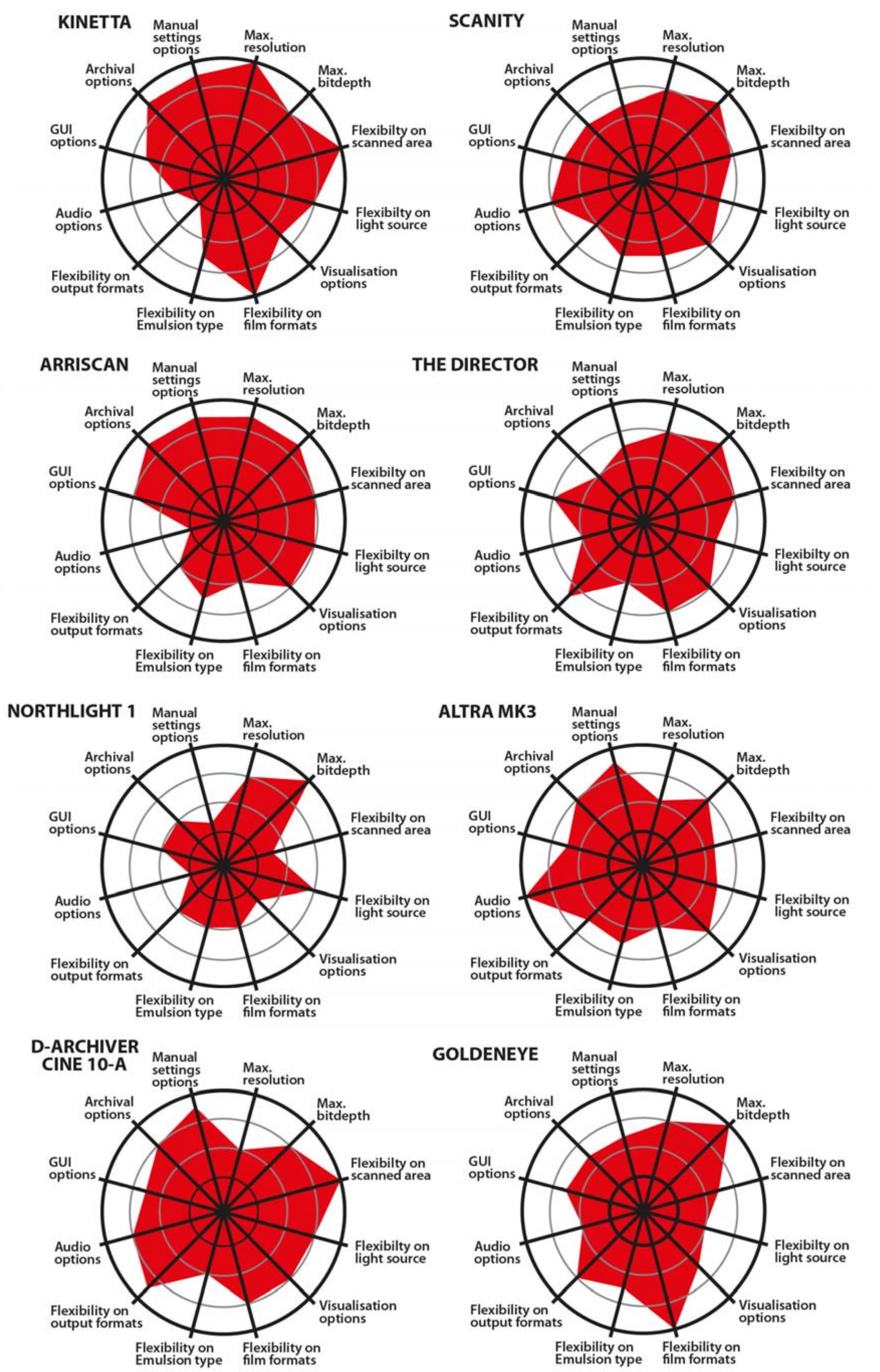


Figure 70 Comparison of the technical specifications of the scanners in an overview

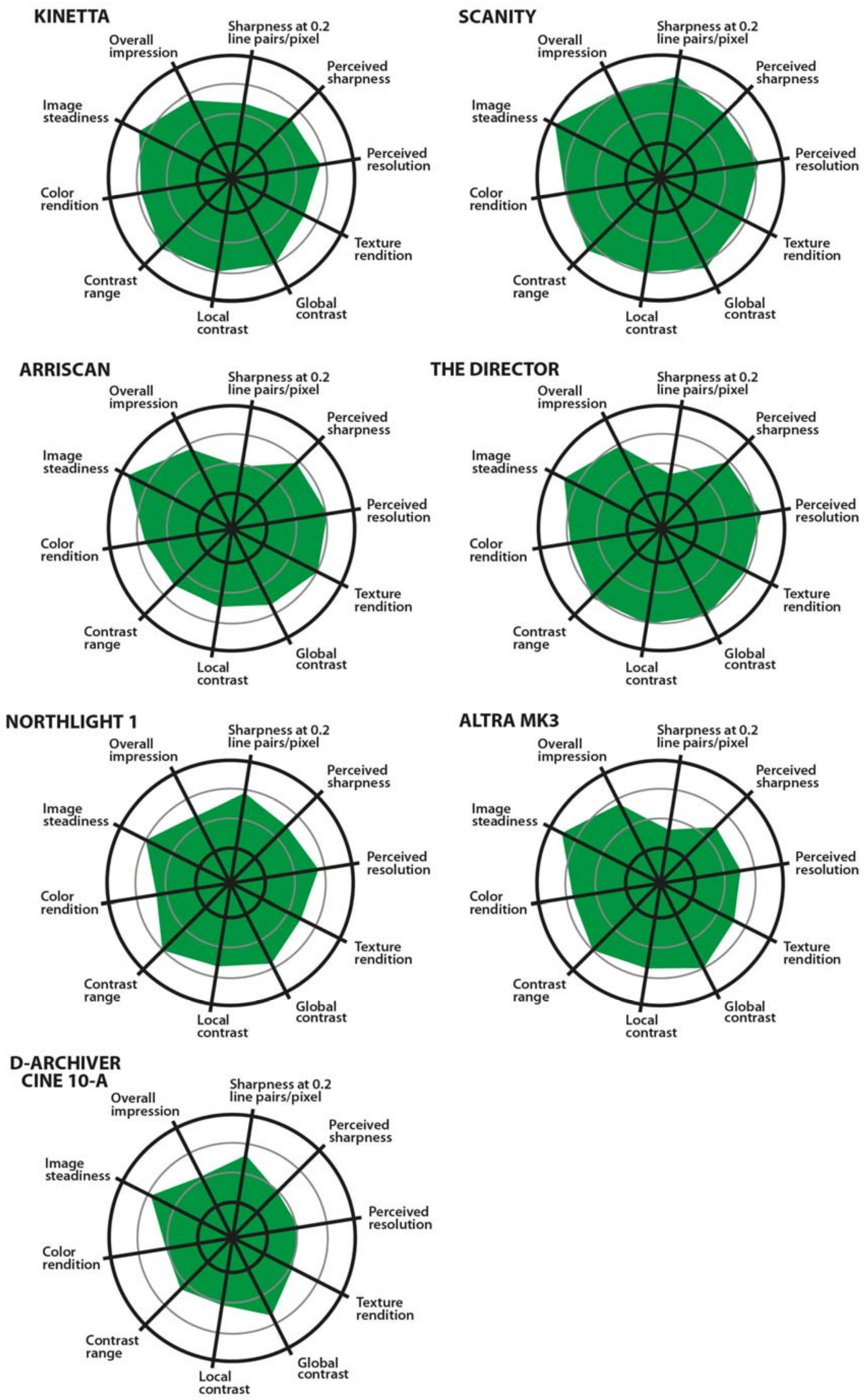


Figure 71 Overview of the results of the subjective analysis

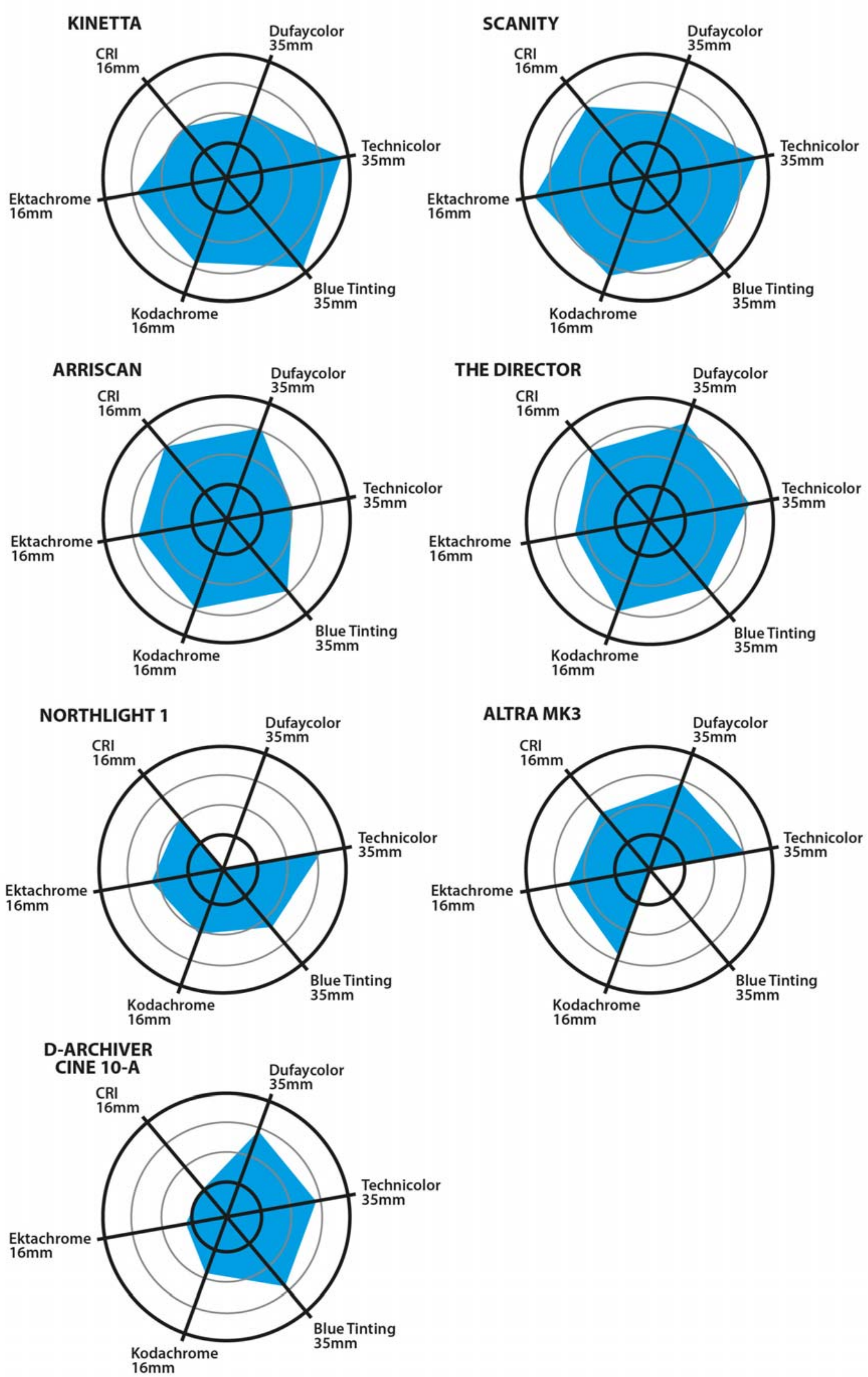


Figure 72 Comparison of the subjective results of the overall impression (Chapter 4.2.3.9)

5 Conclusion and Discussion of Results

In a recent paper submitted to the journal *The Moving Image* (Flueckiger et al. 2016), as well as in our paper presented at the *Colour Fantastic Conference* (2015) we elaborated our unique approach to the digitization and restoration of archival films. We call it a material-based, non-destructive and scalable approach, because it combines a deep investigation of the films' material properties with aesthetic research, technical advancements and custom-tailored IT solutions, while at the same time considering real world conditions in commercial facilities and currently applied workflows. Thus we integrate a variety of perspectives in a pragmatic framework applicable within current archival practices.

One of the most elementary, but often disregarded guiding principles is an understanding of the general constraints and limitations of digitization:

Every digitization is a reading under certain conditions.

These conditions are connected in part to the physical and mechanical principles as introduced earlier (see *Principles of Material–Scanner Interaction*, pp. 10) in part guided by the curatorial decisions or the settings chosen by the scanner operator. Therefore, we developed and applied a three pillar model:

1. Photographic documentation plus analysis of dyes or color compounds
2. Research on stability and decay models of dyes and color compounds
3. Film historical and aesthetic analyses, study of written historical sources

While no available scanner is able to capture a film as it would look on the cinema screen—and there has never been a standard practice for projections either—we should consider scanning primarily as the gathering of information, based on the first pillar: the material analysis mentioned above (see also Flueckiger 2012, Flueckiger 2015 and Trumpy/Flueckiger 2015, Flueckiger et al. 2016). Secondly we must investigate and understand the fundamental difference between information and appearance. When we understand scanning as the gathering of information, we must connect this information to an aesthetic reference that represents a model of appearance. In some cases this might be a film print that is not faded, and this print must be documented photographically in a calibrated workflow or projected on the screen during color grading if the film is not a nitrate print. Furthermore, the unique appearance of a film must be connected to an aesthetic analysis of a group of films produced during the same period, ideally in similar production workflows and on the same film stock. As a result there is not one reference that should guide the reconstruction of a film's appearance, but a multitude of references.

One of the most important factors for a film's appearance is illumination. In contrast to scanners, film projectors use a collimated light source with various characteristics, depending on the time of their use. In earlier decades projectors used carbon arc illumination, with different types of spectral characteristics and color temperatures (see for instance Bowditch et al. 1938 or Schmidt et al. 1943). Film restorer João de Oliveira has long pointed out that we should investigate these practices and take them into account for film restoration (Busche 2006:

14). The Callier effect, mentioned in the chapter *Tinting* (p. 18), is crucial for silver containing materials, especially tinting, but also for a variety of other color stocks. To understand the effect on appearance of the Callier effect, we undertook a variety of tests and watched the tested film samples on different projections. Some of these tests are described in "Color Analysis for the Digital Restoration of DAS CABINET DES DR. CALIGARI" (Flueckiger 2015) where we documented the appearance under several illumination conditions. Furthermore, we projected the film samples in the cinema of Lichtspiel in Berne on November 5, 2013 using different projectors with halogen and xenon light sources. For the immediate side by side projection of the analog with the scanned versions of the film we installed an ARRI LocPro 35 mobile projector in our partner Cinegrell's color grading suite. Illumination levels were adjusted to 48 candela (cd) on both projectors (Figure 73).

Figure 73 Smart phone photo of side-by-side comparison: LocPro projection of Technicolor film (left) vs. scan (right)

As a general rule, the projected analog films showed much more dynamic range, for instance with Technicolor especially in the dark image areas where details were still visible in projection. In accordance with the Callier effect due to the collimated light on the analog projector, small scale contrast was pronounced, therefore the images looked sharper on the screen, especially in the mid-tones. As a result, both the texture of the film's graininess and color appearance varied greatly with projected light as compared to the digital projection. Furthermore, in Lichtspiel's projection we unsurprisingly experienced a high degree of influence due to the illumination levels on dynamic range and overall color appearance. For example, the high contrast in the Kodachrome sample led to overblown highlights on the Kinoton FP38 Xenon projector. One of the drawbacks of collimated projection light is the perceptual magnification of scratches and dirt. This is one of the reasons why scanner manufacturers prefer to apply diffuse light sources in their machines. The diffuse light source operates like a wetgate by reducing the visibility of scratches in particular. A drawback, however, is that the diffuse light source also reduces the mid-tone contrast and the overall dynamics.

Among the most important outcomes of this study is the insight that there is no scanner currently on the market that is able to process every type of historical film stock. Many of the scanners have great difficulties with early applied colors and some are close to unable to scan dense film prints, presumably because these fields of application were never targeted in the first place. Knowledge about historical film stock and about scanners is thus paramount for achieving adequate results.

The specific requirements for an ideal scanner for the digitisation of archival film can be outlined as follows:

1. **Mechanical layout:**
   The scanner should be equipped with a mechanical layout that prevents delicate archival footage from physical damage. This means, among other things, a short film path within the machine and no narrow angles around pulleys (that is, pulleys with sufficient radii). Optional sprocketless transport and manual control of the tension on the film are desirable as well. A flatbed horizontal orientation makes it easier to handle warped film material that results in soft reels. Optional frame by frame transport allows for capturing images with a series of light intensities (HDR) or of multiple spectral bands. A wet gate is desirable for the reduction of digital retouching.
2. **Illumination:**
   The scanner should be an adaptable multispectral imaging system. It should be possible to choose on a case-by-case basis, depending on the optical characteristics of the film scanned, the number of spectral bands, their bandwidths and their positions. This can be done with a multi-element light source (e.g. LED array), with a filtering system (e.g. tunable interference filters) or with a tunable light source such as laser. Ideally the light intensities of the different spectral bands should be independently adjustable. A flexible optical setup should allow varying the arrangement of the light rays, switching between collimated and diffuse illumination.
3. **Resolution and image geometry:**
   The scanner should capture the full film width edge-to-edge at a resolution that will allow the film image area to be reproduced in sufficient resolution (min. 2K for 16mm and min. 4K for 35mm, other formats accordingly). Such an image geometry is essential to preserve metadata such as edge codes and foot numbers in the perforation area.
4. **File output:**
   Furthermore the image data should undergo as few processing steps as possible before output; therefore a Bayer sensor should be avoided, since debayering reduces the rendition of detail.
5. **Modular set-up:**
   A modular setup generally facilitates swapping components to adapt to different formats or other special needs. Manually adjustable controls on all levels allow the experienced user to have maximum control.
6. **User interface and controls:**
   The GUI should offer several layers of in-depth control that can be accessed or

ignored depending on the complexity of the material to be processed. A range of alternative visual signal controls, such as a waveform or a histogram display, are also essential tools to optimize data acquisition.

Whatever decisions are taken during the restoration process, according to restoration ethics they should be transparent—well grounded and inter-subjectively accessible—they should be carefully documented in human readable texts, and they should be reversible. Storing the unprocessed raw scanning data is therefore a basic necessity. With the information–appearance model we make sure that the scan aims at capturing as much information from the film element(s) as possible.

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